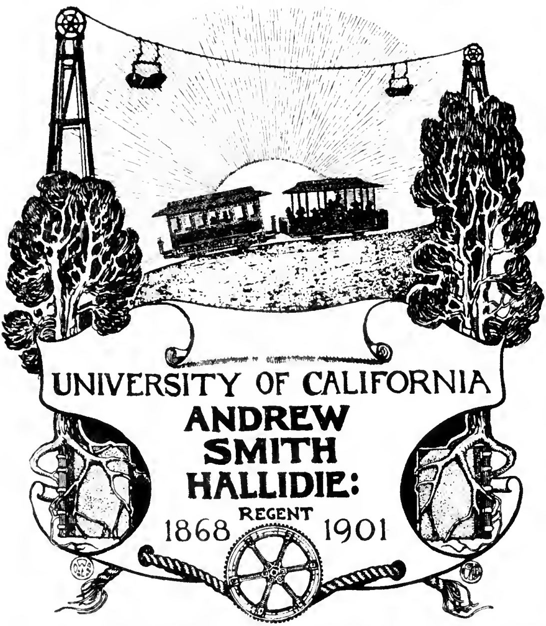

UNIVERSITY OF CALIFORNIA
ANDREW
SMITH
HALLIDIE:
REGENT
1868
1901

Ho[illegible]

Long-Distance Electric Power Transmission

Being a Treatise on the

Hydro-Electric Generation of Energy;

Its

Transformation, Transmission, and

Distribution

BY

ROLLIN W. HUTCHINSON, Jr.

Consulting Electrical Engineer; Associate Member American Institute of Electrical Engineers, and Member of the American Electrochemical Society

LIBRARY
OF THE
UNIVERSITY
OF
CALIFORNIA

NEW YORK:

D. VAN NOSTRAND COMPANY

23 MURRAY AND 27 WARREN STS.

1907

TK1001
H8

Copyright, 1907,
By D. VAN NOSTRAND COMPANY

PREFACE

SINCE the beginning of the twentieth century the development of water-powers for long-distance transmission which began with the famous Frankfort-Lauffen transmission in Germany, in 1891, has been so rapid, and has been marked by such startling feats of engineering skill, that it is almost impossible, except to those who have been intimately connected with this field of engineering, to have more than a vague knowledge of the physical features of such plants.

The author has been encouraged to write the book by the demand of engineers and students for information in concise and convenient form, on the kinds of machinery and apparatus used in hydro-electric, high-tension engineering, and the construction and operation of high-potential transmission properties. While primarily intended as a book of reference for engineers and a text-book for students, it is believed that with the exception of some portions it can be intelligently read by those educated persons who are seriously looking for information on this fascinating branch of applied science. The book does not claim to present anything new, nor does it claim to be an exhaustive treatise on the subject. Indeed, the field of high-tension power transmission is so large that it is impossible to give more than a *résumé* of the subject within the compass of this work.

The first three chapters are devoted to a brief discussion of the salient principles involved in the construction and

158898

operation of the hydraulic end of high-tension generating plants. Elementary mathematics is employed, and frequent reference has been made to the classic of Merriman, "Hydraulics."

In the chapters on generators and the laws involved in transmission, the treatment is rather succinct, and presupposes a knowledge of alternating currents and polyphase machinery.

The art is undergoing such a rapid evolution that the author will warmly appreciate any suggestions from readers on improvements in apparatus treated since the material was prepared.

To those manufacturers who have courteously given information on, and loaned electrotypes of, their apparatus, the author desires to express his hearty thanks.

Chicago, August, 1906.

ERRATA

PAGE 114. Read "several curves of an 1850-k.w. machine."

PAGE 164. Read $L = \frac{dt}{dI}, \; L = \frac{dt}{dI_e}$.

PAGE 208. Read "five kilovolts," "fifty kilovolts."

PAGE 258. "Three kilovolts" should read "thirty kilovolts."

PAGE 317. Omit "per annum," second line from bottom of page.

PAGES 322, 323, 324. All values expressed in kilovolts should read ten times larger; thus, "four kilovolts" should be "forty kilovolts," "five kilovolts" should be "fifty kilovolts," etc.

CONTENTS

LIBRARY OF THE UNIVERSITY OF CALIFORNIA

LONG-DISTANCE ELECTRIC POWER TRANSMISSION

CHAPTER I

LAWS OF HYDRAULICS

THE energy of water is usually expressed in two ways; namely, potential energy and kinetic energy. Water weighing W pounds raised to a height h contains an amount of potential energy equal to the product of the two components, thus,

$$Wh = \text{Potential energy.}$$

When a volume of water is dropped from a known height, it acquires an amount of kinetic energy proportional to the square of the velocity attained by it in falling; thus,

$$W\frac{v^2}{2g} = \text{Kinetic energy}$$

in which $W =$ the weight of the water and $v =$ the velocity of its descent in feet per second.

According to the laws of the conservation of energy the potential energy must equal the kinetic energy, or

$$Wh = W\frac{v^2}{2g}; \quad \text{hence } h = \frac{v^2}{2g}.$$

Head and Pressure. — The surface of calm water is perpendicular to the direction of gravitational force. For

bodies of water of small area, this surface may be conveniently regarded as a plane. Any distance or depth measured below this plane is termed a "head." The head upon any point is its perpendicular depth below the level surface.

Call h the head and w the weight of a cubic foot of water. At a depth h each horizontal square unit has upon it a pressure equal to the weight of a column of water of a height h, and a cross-section of one square unit, or wh. But since the pressure at this point is exerted in all directions with the same intensity, the unit pressure at the depth h is wh. Conversely, the head for a unit pressure p is $\frac{p}{w}$, hence

$$p = wh \text{ and } h = \frac{p}{w}.$$

When h is given in feet and p in pounds per square foot these equations reduce to $p = 62.5\ h$, and $h = 0.016\ p$ (62.5 being the mean value of w).

It is obvious that head and pressure are readily convertible, one into the other. It is a common error to use one term as synonymous in meaning with the other: in reality, each is proportional to the other. It is convenient to remember that one foot head is equivalent to a pressure of 0.434 pounds per square inch; and that a pressure of one pound per square inch is equivalent to a head of 2.304 feet.

Laws of Falling Bodies. — In a perfectly smooth, inclined channel or conduit, water would flow with a constantly increasing velocity, and would, therefore, obey the same laws which govern a body moving down an inclined plane.

A flow under such conditions is never realized in practice, since all surfaces over which water moves are more or less

rough. The motion due to gravity is retarded by the friction between the water and the irregular surfaces over which it flows; hence the theoretical velocities developed by the following equations cannot be equaled by the true or actual velocities.

If a body of water or any other substance, at rest above the surface of the earth and contained in a vacuum, is allowed to fall, its velocity at the end of one second will be g feet (the mean value of g being 32.16); and at the end of t seconds its velocity will be the product of the two, or

$$V = gt.$$

The distance through which the body passes in the time t, is the product of the mean velocity $\frac{1}{2}V$ and the number of seconds, or h (the distance) $= \frac{1}{2}gt^2$.

Transposing to eliminate t, the relations between distance h and velocity V become,

$$V = \sqrt{2gh} \text{ and } h = \frac{V^2}{2g}.$$

If a body is falling with a velocity V_1 at the commencement of a period of time t, its velocity at the expiration of this time will be

$$V_2 = V_1 + gt,$$

and the distance through which it will fall in that time is

$$h = V_1 t + \tfrac{1}{2}gt^2.$$

Eliminating t in the equations, the relations become

$$V_2 = V_1 + \sqrt{2gh}$$

and

$$h = \frac{(V_2 - V_1)^2}{2g}$$

which equations hold good irrespective of the direction of the initial velocity V_1.

Flow from Orifices. — If an opening or orifice is made at any point in the base or sides of a vessel filled with water, the water issues from the orifice with a velocity which depends on the head, the velocity increasing with increase of head.

The law of the theoretical velocity of flow is that enunciated by Torricelli in 1664, viz : The theoretical velocity of flow from an orifice is that which will be attained by a body falling from rest in a vacuum through a height equal to the head of water on the orifice.

Hence, regardless of the plane in which the orifice lies, — whether it be vertical, horizontal or inclined,— if the head be sufficiently large to exert practically a uniform pressure on all sections of the orifice, the equations expressing the relations are

$$V = \sqrt{2gh},$$

and

$$h = \frac{V^2}{2g};$$

the first of which applies to the theoretical velocity of flow that will be given by a definite head ; the second, to the theoretical head which will be produced by a given velocity. The latter expression is usually designated the "velocity head."

Discharge from Small Orifices. — In hydromechanics the word "discharge" is defined as the quantity of water which flows in one second from an orifice, or pipe. The theoretical discharge is commonly represented by the letter Q, and is the discharge as calculated by ignoring the retardation due to frictional resistance.

If every filament of water composing the issuing jet has

the same velocity, the quantity of water which issues in one second is equivalent to the volume of a prism having a base of the same dimension as the cross-section of the stream, and a length equal to its velocity. Representing this area by a and the theoretical velocity by V, the theoretical discharge is given by the equation

$$Q = aV.$$

If a be taken in square feet and V in feet per second, the value of Q will be in cubic feet per second.

If the orifice be of small area, and the head h the same at all points of the opening, the discharge will be (theoretically)

$$Q = aV = a\sqrt{2gh}.$$

This equation is strictly applicable only to orifices which lie in a horizontal plane and on which the head is constant. The error involved by applying it to vertical orifices, however, is less than one-half of 1 per cent if h be greater than twice the depth of the orifice. When the equation is applied to a vertical orifice, h must be taken as the vertical distance from the center of the orifice to the free water surface.

The Energy of a Jet. — If a stream of water has a velocity V, and if W be the weight of water per second which passes any given cross-section, the kinetic energy possessed by this moving water is the same as will be stored up by a body falling freely under the influence of gravity through a height h, and attaining thereby a velocity V.

Calling E its kinetic energy,

$$E = Wh = W\frac{V^2}{2g}.$$

Hence, if the quantity of water passing through any given cross-section of the jet be constant, the energy of the jet is (theoretically) proportional to the square of its velocity.

It is evident that the weight W of the water may be expressed in terms of the area or cross-section of the jet and its velocity. Designating the cross-section of the jet in square feet by the letter a, and the weight of a cubic foot of water by w,

$$E = \frac{Wa V^3}{2g},$$

from which it is obvious that the energy or work which a jet is capable of performing (theoretically) varies as the cube of its velocity.

The energy of a jet is always the same, irrespective of the direction in which it is moving — whether horizontal, vertical, or inclined. Its energy per second is under all conditions Wh, in which h is the velocity head corresponding to the actual velocity V, and W the weight of water discharged per second. Since the theoretical velocity V generally exceeds the actual velocity, the energy of a jet should never be calculated from the theoretical velocity.

Impulse and Dynamic Reaction of a Jet. — If a jet delivers W pounds of water per second at a uniform velocity V, the motion of such a stream may be considered as due to a constant force F, which acts for one second on the weight W, and is then withdrawn. During this interval of time the velocity of the water W increases from zero to a value V, and the average velocity is $\frac{1}{2}V$. Therefore, the work $F \cdot \frac{1}{2} V$ is given to the water by the force F. The kinetic energy of the flowing water is $W\frac{v^2}{2g}$; and

by the law of the conservation of energy, the magnitude of the constant force is

$$F \cdot \tfrac{1}{2} V = W \frac{V^2}{2g},$$

which reduces to

$$F = W \frac{v}{g}.$$

It is apparent that the expression $W \frac{v}{g}$ is the same as that for momentum; and as W may be written WaV (w being the weight of a unit of water and a the area of the orifice), the equation resolves into the form:

$$F = \frac{WaV^2}{g};$$

and since

$$\frac{v^2}{2g} = h,$$

$$F = 2Wah,$$

in which the value of F is termed the impulse of the jet. Since the values of W, V, and g are in pounds and feet per second respectively, the value of F is also expressed in pounds.

In hydromechanics the word "impulse" has a different meaning from its definition in mechanics as the product of force and time.

Since W in hydraulic computations is expressed in pounds per second, the impulse will also be expressed in pounds.

If any surface, as, for instance, the vanes of a water-wheel, be placed in the path of the jet, the impulse may be considered as a pressure which sets up a rotation of the wheel.

If a jet is caused to impinge normally on a plane it produces a pressure on the plane which corresponds to the impulse F, because the force necessary to stop W pounds of water in one second is the same as that which was required to produce its motion.

Likewise, if a jet, which is moving with a velocity v_1, suffers a retardation by which its velocity is reduced to v_2 within one second, the impulse in the first second of time is $W\frac{v_1}{g}$, and in the next second, it is $W\frac{v_2}{g}$.

The difference between these two, or

$$F_1 - F_2 = W\frac{(v_1 - v_2)}{g},$$

is the dynamic pressure developed. Upon this principle depends the operation of turbines or other hydraulic machines.

Constant Flow in Smooth Pipes. — When water flows through a pipe of irregular cross-section, every section of which is filled with water, a like quantity of water passes each section per second.

Designating the quantity of water by q and the mean velocities by v_1, v_2, and v_3 in sections having areas a_1, a , and a_3 respectively, the flow is given by the equation,

$$q = av = a_1 v_1 + a_2 v_2 + a_3 v_3 \ldots$$

(The velocities in different sections vary inversely as the areas of the sections.)

Call W the weight of water which flows per second through the sections of the pipe a_1 and a_2, and let v_1 and v_2 be the mean velocities in these sections. In the section a_1 the potential energy possessed by the water when at rest is Wh. When motion is imparted to it, the energy in that

section is the potential energy Wh, due to the head pressure plus the kinetic energy

$$W\frac{V_1^2}{2g} = W\frac{[V_2^2 + h]}{2g}.$$

Ignoring the losses due to impact or friction, the energy in both cases is the same, hence,

$$H_1 = h_1 + \frac{v_1^2}{2g}, \text{ and } H_2 = h_2 + \frac{v_2^2}{2g},$$

H being the hydrostatic head at no flow. The law represented by this equation was first established by Bernouilli, and may be stated as follows:

At any section of a tube or pipe, in which the flow is steady and frictionless, the pressure head plus the velocity head equals the hydrostatic head which exists when there is no flow.

In applied hydraulics this theorem is of very great importance.

Definitions of Coefficients of Contraction, Velocity, and Discharge. — A jet of water issuing from an orifice suffers a contraction of area, due to the fact that the filaments of water approaching the orifice move along constantly converging lines.

This convergence continues for a slight distance beyond the plane of the orifice.

The contraction of the jet causes only the inner corner of the orifice to be struck by the issuing water. (It is this phenomenon which causes a jet issuing from a cylindrical orifice to have the appearance of a clear crystal bar.) A contraction of the issuing stream also takes place when an irregular or triangular orifice is used

The *coefficient of contraction* may be defined as the number by which the area of the orifice must be multiplied to give the area of a section of the jet at a distance from the plane of the orifice equal to approximately one-half its diameter.

Denoting the coefficient of contraction by c_c and the area of the contracted section of the issuing jet by a_c, then

$$a_c = c_c a,$$

the value of which is always less than unity.

The coefficient of contraction can be directly determined by measuring with calipers the dimensions of the least

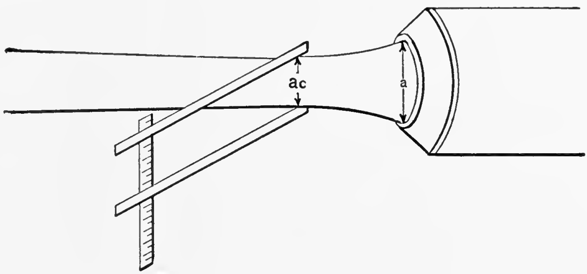


Fig. 1. Measurement of Coefficient of Contraction

cross-section of the jet. Fig. 1 shows the method of making the measurement. For a circular orifice having diameters for sections a and a_c, d and d_c respectively,

$$c_c = \frac{a_c}{a} = \left(\frac{d_c}{d}\right)^2.$$

A common mean value for the coefficient of contraction is 0.62, which means that the minimum cross-section of the jet is 62 per cent of that of the orifice.

The *coefficient of velocity* is the constant by which the theoretical velocity of flow from the orifice must be multi-

plied in order to give the true velocity at the smallest cross-section of the jet.

Let c_v be the coefficient of velocity, V the theoretical velocity due to the head, and v the actual velocity at the contracted section, then,

$$V = c_v v = c_v \sqrt{2gh}.$$

The coefficient of velocity is always less than unity, since it is impossible for gravitational force to generate a velocity greater than that due to the head.

A mean value that is commonly employed is 0.98, which means that the actual velocity of flow at the contracted section is 98 per cent of the theoretical velocity.

The *coefficient of discharge* is the constant by which the theoretic discharge must be multiplied in order to give the actual discharge.

Calling c_d the coefficient of discharge, Q the theoretical and q the actual discharge per second, then,

$$q = c_d Q.$$

The coefficient of discharge may be accurately determined by permitting the flow from an orifice to fall into a receptacle having a constant cross-section, and measuring the height of water by a hook gauge.

Then q being determined and Q calculated from the formula for theoretic quantity,

$$c_d = \frac{q}{Q}$$

Influence of Suppression of the Contraction. — If the lower edge of a vertical orifice is near the bottom of a reservoir, the issuing filaments of water from its lower portion travel in lines almost perpendicular to the plane of the opening, and hence there is no contraction of the jet on

the lower part. This phenomenon is termed suppression of the contraction. It also occurs when the lower edge of

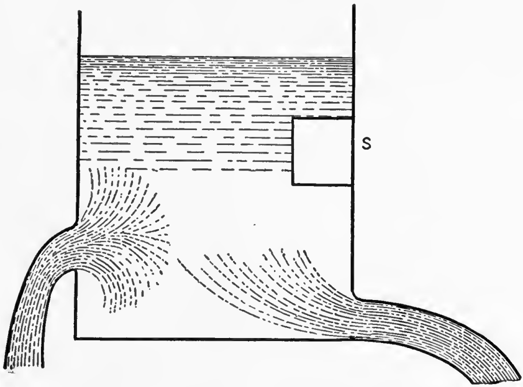


Fig. 2. Suppression of Contraction of Jets

the orifice is slightly above the bottom, as shown in Fig. 2, but is smaller in this case.

Should the orifice be located so that one of its vertical edges is at or near the side of a reservoir, as at *S*, the jet has its contraction suppressed on only one side.

If one of the vertical edges of an orifice is located at the lower corner of a reservoir, the jet is suppressed in its tendency to contract both upon one side and upon its lower portion.

Suppression of the contraction of a jet is undesirable since it increases the cross-section of the jet at a point where complete contraction would otherwise occur. This increases the discharge to an extent depending on whether the suppression takes place on one or two sides.

Lesbros and Bidone have shown that for square orifices, with contraction suppressed on one side, the coefficient of

discharge is increased nearly 3.5 per cent; with contractions suppressed on both sides nearly 7.5 per cent.

For rectangular orifices the increase in the coefficient of discharge from this cause varies from 6 to 12 per cent, depending upon the ratio of length to height.

Flow from Circular Vertical Orifices. — If a circular vertical orifice of a diameter d, discharges water which has a head h on the center of the orifice, then the mean velocity (theoretical) $= \sqrt{2gh}$; and the theoretical discharge ($Q = av$) is

$$Q = \frac{\pi}{4} d^2 \sqrt{2gh} = 6.3\, d^2 \sqrt{h},$$

which is only applicable when h is quite large compared with d.

Flow from Rectangular and Square Vertical Orifices. — When the dimensions of an orifice in the side of a chamber filled with water are small as compared with the head, the velocity of outflow is $\sqrt{2gh}$, h being the head on the center of the opening.

Under such conditions the theoretical discharge from a rectangular vertical orifice is

$$Q = bd\sqrt{2gh},$$

in which b is the width and d the depth of the orifice. In general, the equation for actual flow from a square vertical orifice is

$$q = c_d b^2 \sqrt{2gh} = 8.02\, c_d b^2 \sqrt{h},$$

in which c_d is the coefficient of discharge and b is the side of the square.

In case h is smaller than about twice the side of the orifice, the formula for accurate determination of q is

$$q = 5.347\, cb\, (h_2^{\frac{3}{2}} - h_1^{\frac{3}{2}});$$

and since the linear dimensions are in feet, the value of q will be in cubic feet per second.

Measurement of Water by Orifices. — The use of orifices for accurately measuring water demands many precautions. It is essential in the first place that the area of the orifice be small compared with the area of the reservoir; otherwise an error is introduced due to velocity of approach.

The inside edge of the orifice should have a right-angled corner of definite dimensions, which must be accurately ascertained. When the orifice is cut in wood it is imperative that the inside surfaces be perfectly smooth and unobstructed with slime. It is especially inadvisable to use orifices under small heads, since slight changes in the head occasion considerable errors in computation. The coefficients of discharge under such conditions also vary quite quickly,

Should the head on the orifice be very low, determinations of the discharge are untrustworthy, owing to the vortices which are set up.

Precise measurements of the head can only be made with the hook gauge.

Weirs. — A weir may be defined as an opening cut in the top edge of the vertical side of a vessel, through which water issues. The opening is usually of rectangular shape, and, unless otherwise stated, a weir may always be assumed to have such a shape that the lower edge is truly horizontal and the sides vertical. The term "crest" is applied to the horizontal edge of the weir.

Weirs are separated into two general classes: weirs with end contractions and those without such contractions.

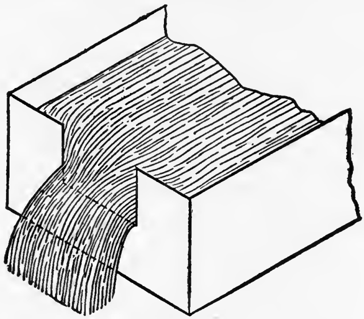


Fig. 3. Weir with Contracted Ends.

Fig. 3 shows the more common type of weir, with the ends contracted. In this form the vertical sides of the opening are cut away a sufficient distance so that both sides of the weir are thoroughly contracted.

In Fig. 4 the edges of the opening coincide with the sides of the feeding trough, which causes the filaments of

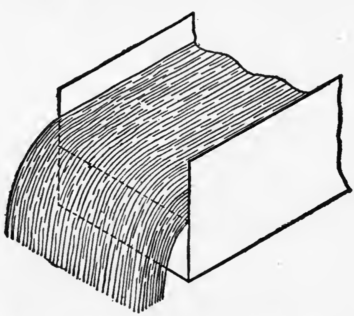


Fig. 4. Weir without Contracted Ends.

water against the sides to pass over the crest without suffering deflection from the perpendicular planes in which they are moving.

In order to obviate error due to suppression of the contraction, the distance from the crest of a weir to the bottom of the supplying channel or reservoir should be three times the head of water on the crest. This rule is also applicable to weirs with end contractions.

Weirs are extensively used in determining the flow of small streams and for ascertaining the quantity of water delivered to hydraulic motors.

On account of the smallness of the head on the crest of the weir, it is essential to determine it with accuracy in order to obviate an error in the calculated discharge. To ascertain the head on the crest of the weir, the measure-

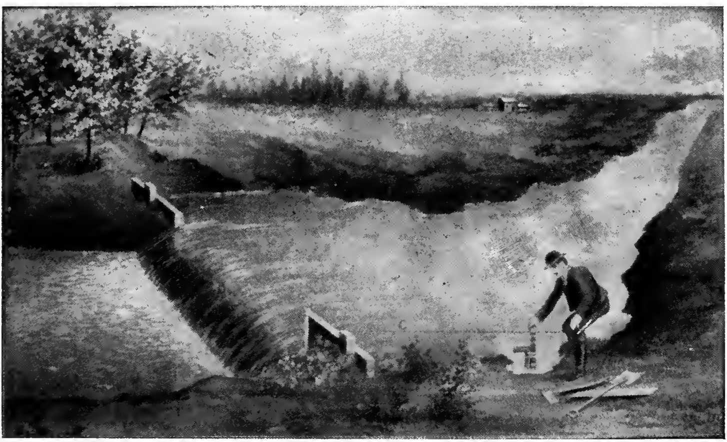


Fig. 5. Method of Making Weir Measurement of Streams

ment is taken several feet up stream, as indicated in Fig. 5, in order to prevent the error which the curve taken by the surface of the water introduces.

Various conditions of flow and surface contour determine

the distance up stream to which the curve will extend. As a general thing, level water is to be had at a distance of about 3 feet from the crest of the weir, in case the weir is a small one. If the weir is large, the length of the curve from the crest up stream varies from 5 to 9 feet.

In the majority of observations to determine the discharge of weirs, the water possesses a considerable velocity of approach at the point where the head H is recorded by the hook gauge.

Call v the velocity in the supplying canal at this point (Fig. 5), and consider such velocity as being due to a head h from a body of calm water some distance up stream from the recording instrument. Evidently the actual head on the crest is $H + h$, since the measuring device would have recorded such a value if it had been located at a point where the velocity was nil.

Hence the discharge Q is (theoretically)

$$Q = \tfrac{2}{3}\sqrt{2g} \cdot b(H + h)^{\frac{3}{2}}$$

where H is the reading of the gauge, and h is a value to be computed from the velocity v.

Both the contraction of the stream and the friction of the weir edges modify this equation appreciably, so that the expression giving the actual discharge becomes :

$$q = c_d \tfrac{2}{3}\sqrt{2g} \cdot b(H + sh)^{\frac{3}{2}}$$

in which s is a constant, the value of which ranges from 1.0 to 1.5.

If the ends of the weir are contracted, and if the velocity of approach is zero, the discharge per second is

$$q = c_d \tfrac{2}{3}\sqrt{2g} \cdot b H^{\frac{3}{2}}.$$

In case there is a velocity of approach v at the recording device, the expression giving the discharge becomes :

$$q = c_d \tfrac{2}{3} \sqrt{2g} \cdot b (H + 1.4 h)^{\frac{3}{2}}.$$

Hydraulic Measuring Instruments. — The instruments commonly used in hydraulic measurements are the *hook gauge*, the *piezometer* or *pressure gauge*, the *differential pressure gauge*, the *current meter*, the *water meter*, the *steel tape*, *level* and *transit*.

The hook gauge consists of a graduated metallic rod moving in a vertical plane in fixed supports, and fitted with a vernier by means of which readings can be made to thousandths of a foot. To the lower end of the rod is attached a sharp pointed hook which is raised or lowered by turning the vernier until the point of the hook is exactly at the water level.

In making readings with the hook gauge the point of the hook is lowered slightly below the surface of the water by actuating the screw at the upper part of the device. When the point has almost pierced the skin of the water surface a slight bulge or protuberance manifests itself. To prevent a fictitious reading the point is lowered until the bubble or pimple is just visible to the eye.

The principal use of the hook gauge is for ascertaining the height or head of water on the crest of a weir. In such cases the heads of water are slight, and hence must be precisely determined. The most accurate gauges are graduated to read in ten thousandths of a foot. Fig. 6 shows a hook gauge.

The piezometer or pressure gauge is a device for recording the pressure of water in a pipe. A common form of piezometer consists of a dial graduated to read in pounds

per square inch and fitted with a movable pointer. Its principle of operation is analogous to the Bourdon steam gauge. A small coiled tube closed at one end is placed in a containing case. The other end of the tube is joined to the opening through which the water is introduced. When subjected to water pressure the tendency of the tube is to straighten; hence the closed end moves, and by doing so actuates the pointer which is attached to it. When the pressure is removed the tube returns to its normal position. If the water pressure is very high the Bourdon type of gauge becomes impracticable, a mercury gauge being generally employed in such cases.

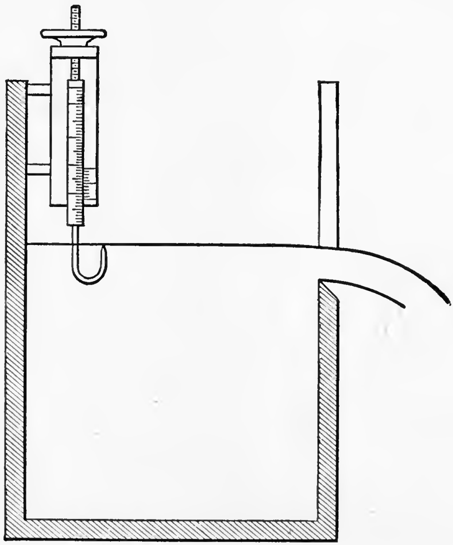


Fig. 6. Hook Gauge

A differential pressure gauge, as the name implies, is a device for measuring differences of head or pressure. In its simplest form the instrument consists of a vertical scale graduated in practical fractions and rigidly attached to a fixed support. The water columns, of which the heads are required to be determined, are led by means of curved tubes to the sides of the scale and their differences of head read on the scale.

When the heads are quite high a mercury differential gauge is employed. This consists of a *U*-tube (open at the top) to which is joined at the horizontal part of the *U* a vertical tube (see Fig. 7). This attached tube is fitted with a stopcock, as are also the limbs of the *U*-tube.

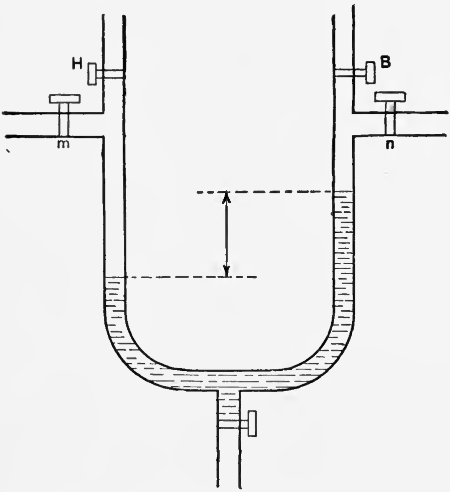


Fig. 7. Differential Mercury Gauge

The uppermost of the stopcocks being open, the mercury is poured in through the top (*m* and *n* being closed). The mercury stands at the same level in each tube. Cocks *B* and *H* are then closed and *m* and *n* are opened. Water rushes in through *m* and *n*, and the mercury column is lowered in one tube and raised in the other. From the difference between the heights of the mercury columns the differences in heads are determined. In mercury gauges of both types (the piezometer and differential), the specific gravity of the water and mercury at various temperatures is required to be known. The gauges must also be calibrated over that part of the scale where readings are to be made.

The current meter is virtually a small windmill fitted with several vanes mounted on a spindle. The faces of the vanes are so placed that normally the pressure of the cur-

rent is directed against the vanes and causes them to revolve at a speed proportional to the velocity of the current. In very accurate instruments the number of revolutions in a definite time is recorded by an appliance located either in a boat or one on bank of the stream. From the base used, wires carrying an electric current are led to the meter under water. Electrical connection is made and broken at every revolution, and so cause a dial to be actuated on the recording device. From the number of revolutions registered in a given time the observer computes the mean velocity of the stream. The Price type of current meter, which is commonly employed in America, is shown in Fig. 8.

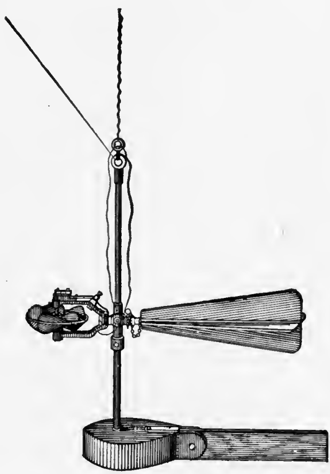


Fig 8. The Price Current Meter

The water meter is a device for measuring the quantity of water supplied to an hydraulic motor or to a building or factory. Meters for this purpose operate on the displacement principle; that is, water in passing through the meter moves either a valve or a piston, or perhaps a wheel; the motion being transmitted through a clockwork mechanism to dials which are calibrated to record the quantity passed through in any given time. Water meters are of the piston type, screw type, or rotary type. In the piston type of meter the flow of water forces two pistons to move in opposite directions, the water being admitted and discharged through ports in the cylinder which are opened and closed

by slide valves. The rotary meter consists of a wheel which is so fitted in a case that it is caused to rotate when the water passes through. The screw meter consists of an inclosed helical member which is caused to revolve on its axis by the entering water.

CHAPTER II

APPLIED HYDRAULICS

Flow in Streams and Rivers. — Definitions of Wetted Perimeter, Hydraulic Radius and Slope.

Although no branch of hydraulic engineering has had bestowed upon it more diligent scientific investigation than that of the flow in streams and river channels, yet at the present time the subject is but poorly understood.

The desideratum in these investigations and study has been the perfection of a simple method for ascertaining the mean velocity and discharge without necessitating the employment of costly methods of instrument measurements.

The flow in a stream or river is said to be *steady* when the same quantity of water passes each section in one second. When this condition is realized, the mean velocities in different sections vary inversely as the areas of the sections. In the case of steady flow where the sections under consideration are the same in area, the flow is said to be uniform.

When the stream is rising or falling, the flow is said to be non-uniform.

The *wetted perimeter* of the cross-section of a channel is that part of the boundary which is in contact with the water. It is generally designated by the letter p.

The *hydraulic radius* of the cross-section of a channel is its area divided by the wetted perimeter. It is

denoted by the letter r. Calling a the area of the cross-section of a channel, the hydraulic radius $r = \frac{a}{p}$.

The value of r is expressed as a linear quantity in the same units as p. It is not infrequently termed the hydraulic depth, or the hydraulic mean depth, since for a shallow section it varies but slightly from the mean depth of the water.

The *slope* of a water surface in a longitudinal section is the ratio of the fall h to the length l in which that fall occurs. It is usually designated by the letter s. Its value is determined by the equation

$$s = \frac{h}{l}.$$

A precise determination of its value, however, involves a determination of h. This is done by comparing the water level at each end of a line to a bench mark, using a hook gauge or some other accurate method. The benches are connected by level lines carefully run and a length l measured along the inclined channel. This length should be made as long as is consistent with practical conditions, since the longer it is the smaller becomes the relative error in h.

When the slope is zero no flow occurs; but with even a very slight slope the force of gravity supplies a component acting down the inclined surface, and more or less motion follows. It is obvious that the velocity of flow increases with increase of slope.

Determination of the Energy of Streams. — The determination of the energy of a stream involves the measurement of its velocity of flow from which the discharge is computed from the relation $q = av$; or in case of a small

stream by direct measurements of the discharge by means of a weir.

When a dam is thrown across a stream of appreciable size it is possible to use the dam as a weir, provided there is no seepage of water through it. In such a case the coefficients in the equations for waste weirs are used in making the computations.

In the absence of a dam a method of gauging is generally employed. This is considered farther along.

In ascertaining the velocity of flow from which the discharge is calculated, it is customary to employ the float method. The three kinds of floats used are termed *surface floats*, *double floats*, and *rod floats*.

A surface float must be immersed to such a depth that it will completely obey the motion of the upper filaments; and it should be of a form which is not easily affected by the wind.

A double float comprises a surface float and a sub-surface float. The sub-surface float is a smaller surface float which is connected by means of a fine cord or wire to the surface float; the surface float being weighted in order to keep it submerged, and cause it to pull the connecting string sufficiently taut.

It is essential that the surface float be made of a shape that will offer but little resistance to motion. The lower float should be of appreciable size, since the purpose of the combination is to ascertain the velocity of the lower one only.

While this method of double floats is commonly used, it is not to be considered an accurate one, since errors are introduced by the cord friction, and by the velocity of the large float being influenced by the upper one.

The rod float consists of a hollow cylinder of tin, which is weighted to stand vertically at any desired depth by putting in shot or pebbles. When a rod float is employed for making a velocity determination, it should be weighted so as to sink almost to the bottom of the channel.

Velocity observations by means of floats are conducted as follows: A definite length of channel is marked off, and two observers with stop watches are stationed, one at each end, to time the movement of the float past each point. The use of one stop watch is permissible, the passage of the float at each station being signaled by the watchers to a time-keeper.

If l represents the length of the channel and t the time in seconds required for the float to pass over the channel base, the velocity $v = \frac{l}{t}$. When numerous observations are made, the work of division is lightened by using the reciprocals of the values of t and multiplying them by l, which may be an even number.

The velocity of a rod float is said to be the mean velocity of all the filaments of water in contact with it; but this is not true, because the rod moves a trifle slower than the water.

The formula of Francis is perhaps the best empirical one for determining the mean velocity V_m of the filaments between the surface and the bed of a stream from the observed velocity V_f of the rod float. This formula is

$$V_m = V_f(1.012 - 0.116)\sqrt{\frac{D'}{D}},$$

where D is the total depth of the stream, and D' the depth of water below the end of the rod.

A more accurate method than floats for determining the velocities of streams is the use of the current meter. This device is operated from a bridge in the case of small streams or from an anchored boat in a river. This method of gauging the discharge gives more accurate results than can be obtained by any formula.

For making a gauging, a section of channel should be selected where a uniform flow exists. Several sections at right angles to the direction of flow are then chosen, and soundings made upon them at a number of points across the stream, the water gauge being read at each sounding. The distance between sounding points is measured by means of a cord stretched across the stream.

The information is now at hand for obtaining the areas a_1, a_2, a_3, etc., as shown in Fig. 9. The sum of these areas is the total area a.

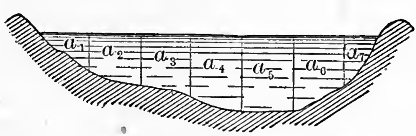


Fig. 9. Method of Determining Total Area of a Stream

In order to obtain the additional areas for a rise of stream, levels should be run beyond the water edge to high-water marks.

When a current meter can be used, it is necessary to make readings only in one section : when floats are used, two or more sections should be selected.

The next step is the determination of the mean velocities v_1, v_2, v_3, etc., in each of the sub-areas. When a current meter is employed, this is accomplished by commencing at one side of a sub-division and slowly moving the meter until bottom is nearly touched ; then moving it a few feet in a horizontal plane and drawing it to the surface ; again moving it a short distance longitudinally and lowering it, and so

on until the entire sub-area has been gone over. The velocity obtained from the total number of revolutions during the time the meter is submerged is the mean velocity for the sub-area.

A common method of making this determination consists in merely raising and lowering the meter in the middle of the sub-area and taking a reading. This gives a fair approximation to the mean velocity.

The areas and velocities having been found, the discharge q is computed by the equation

$$q = a_1v_1 + a_2v_2 + a_3v_3 + \ldots ;$$

dividing this by the total area, a, the mean velocity in the entire section is ascertained.

Rough determinations of velocity can be found by one or several measurements by the use of floats. This method is much less expensive than the other methods given, and where quick and only approximate results are desired is to be recommended.

Experimental work has shown that the ratio of the mean velocity, v, to the maximum surface velocity, V, lies between 0.7 and 0.85 ; calling it 0.8

$$v = 0.08\ V.$$

This assumption gives an error in the value of v which rarely exceeds 18 per cent ; usually the error is much less than this value.

The selection of the particular method to be used in determining the energy of streams should depend upon the conditions. It will be usually found that measurements which give the most accurate results irrespective of expense are the most satisfactory in the long run.

Types of Dams. — Five general types of dams are employed in hydraulic engineering practice: *masonry dams, rock-fill dams, hydraulic-fill dams, timber dams,* and *earthen dams.*

The type of dam suitable for any given condition depends on the character of the foundation which can be secured, the size and importance of the structure which is necessary, the topography of the country, the degree of imperviousness required, and the permissible cost.

The character of structure best adapted to withstand water pressure and the destructive action of the elements is unquestionably the masonry dam founded on solid rock, and built up *in the form of a monolith* between natural rock buttresses on a gorge, with Portland cement mortar.

Masonry dams, however, cannot be erected on every site where it is desired to impound water, since the foundations are not always suitable, and the conditions which must be met render their cost prohibitive.

The general requirements to be met in the design of a masonry dam are: (1) It must not fail by overturning; (2) it must not slide on its foundations or any horizontal points; (3) it must not fail by the crushing of the masonry or by the settlement of its foundations; (4) it must be safe from excessive pressure upon the masonry whether the reservoir be full or empty; (5) certain known safe limits to crushing of the masonry of the class to be used should not be exceeded.

Masonry dams are generally built in the form of a simple triangle with certain modifications, such as a definite width of top to enable the dam to resist wave action and ice thrust.

Masonry dams may resist the thrust of water pressure

either by their weight alone or by being built in the form of an arch which will transmit the pressure to the abutments. The first of these two types is called the "gravity" dam. The second is termed the "arch" dam; and it may be either of the gravity type in arched form, or it may depend upon its arched form alone.

In either case, the weight of the dam must be borne by foundations which must be of the best quality of solid bed rock. Every masonry dam should be built in the form of an arch in order to avoid cracks or fissures in its surface due to changes of temperature. Another advantage of a curved arch dam is that the pressure of the water tends to close all small cracks that occur, and also takes up the movement due to temperature changes without producing cracks.

Wilson says that the pressure on the back of an arched dam is perpendicular to the up-stream face and is decomposed into two components, one perpendicular to the span of the arch and the other parallel to it.

Rock-fill dams find application at the present time in cases where economy is the main consideration. They are largely used in the Western States for reservoir dams when a large supply of stone is available. They are built in six forms: (1) With a facing of asphalt concrete laid on a sloping wall; (2) with a central core of steel plates and hand-laid facing walls; (3) with facing of Portland cement laid on a dry wall; (4) with facing of masonry built vertically and covered on the lower side with blocks of stone laid in mortar; (5) with facing of steel-plates laid on a sloping interior surface on a dry hand-laid wall; (6) with a facing of earth.

Hydraulic-fill dams are the cheapest to construct, and are used in regions where the adoption of a different type

would be prohibitive on account of the topography of the country and the cost of transporting material to the site. The conditions required for the practical employment of hydraulic-fill dams are: (1) An abundance of water at a proper elevation to form a "sluicing head"; (2) sufficient deposits of materials to form the dam, convenient to either end and high enough above the top to permit of the requisite grade for transporting the suspended matter to the desired point; (3) a good foundation, which is requisite for all dams.

Hydraulic-fill dams are constructed by tearing down loosely attached rock, earth, and other organic matter by means of a jet of water under high pressure and allowing it to float to the point where the dam is to be constructed. They are commonly employed in some sections of the West for storage reservoirs. They have been built as cheaply as 65 cents per acre-foot of storage capacity.

Wooden dams are frequently employed when the stream is small, and a supply of timber is readily available. Their chief recommendation is cheapness.

Earthen dams, pure and simple, are seldom used at the present time. Six forms exist: (1) A homogeneous embankment of earth in which all material is alike throughout; (2) an embankment with a central core of puddle consisting generally of a mixture of sand, gravel, and concrete of clay; (3) embankment in which the central core is a wall of masonry or concrete; (4) embankment with "puddle" or concrete placed on the water face; (5) embankment of earth resting against an embankment of loose earth; (6) embankment "sluiced" into position by high pressure. The most popular of these forms is the masonry core wall with "puddle" facing.

Pressure on Dams. Causes of Failure. — In constructing a dam to impound water one of two possible cases exists: In the first the masonry may extend to a considerable distance above the level of the water behind it, the discharge being effected by means of a waste weir. The water pressure against its surface is then in a direction normal to the horizontal plane (Fig. 10). Such pressure may be divided into two composite parts, one part of which lies in a horizontal and the other in a vertical plane. For all practical purposes the horizontal component is the only one which need be considered.

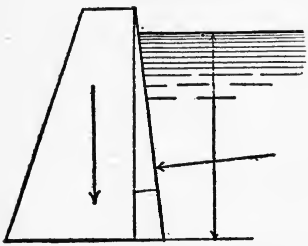


Fig. 10. Direction of Pressures on Dams

Representing this by M and its height above the base of the dam by h, the magnitude of these two quantities for one linear foot becomes

$$M = wh \cdot \tfrac{1}{2} h = \tfrac{1}{2} wh^2,$$

where w represents the weight of a cubic foot of water.

It is obvious that the horizontal component of water pressure does not depend on the slope of the dam.

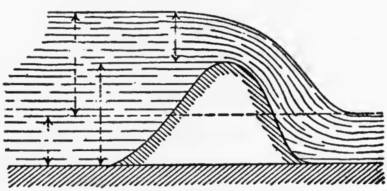


Fig. 11

In the more common case where the water is discharged over the top of the dam (Fig. 11), let h, as before, be the height of the dam and d the depth of water on the crest of

the dam. Then the horizontal pressure against its back will be

$$M = wh\,(d + \tfrac{1}{2}\,h) = \tfrac{1}{2}\,wh\,(h + 2d).$$

Dams burst or fail from the following causes: (1) By sliding; (2) by rotation of the toe; (3) by overturning; (4) by crushing of the material (if of masonry); (5) by settling of the foundations. The first two are the most common causes of failure.

A dam will slide when the horizontal pressure against its surface equals or exceeds its frictional resistance. Calling M the horizontal pressure against a dam, f the coefficient of friction and W_a its weight, sliding occurs when

$$M = f\,W_a.$$

Rotation of the toe of a dam occurs when the moment of M equals the moment of W with respect to the toe. Or, failure from this cause occurs when

$$Ml = W_a a,$$

in which l and a are the lever arms let fall from the toe in the direction of M and W_a respectively.

For masonry dams the maximum permissible pressure should not exceed 15 tons per square foot. In some cases it should not exceed 6 tons per square foot.

A frequent cause of failure in dams where the surplus water is not discharged over the crest is lack of sufficient spillway or waste weirs.

The most notable instance of the failure of a high dam for hydro-electric power development is that of the Austin, Texas, municipal dam. The dam proper was 1,091 feet long and 68 feet high. It was built perfectly straight and con-

tained about 88,000 cubic yards of masonry, of which 70,000 cubic yards was of rough rubble and 18,000 cubic yards of cut stone. The cost of the dam, with the head-gate masonry, was $608,000. It was situated on the Colorado River, two and a half miles above the city.

In a severe flood early in April, 1900 (the highest in the history of the dam), about 500 feet of the structure was pushed bodily down stream, sliding, apparently, on its base.

Storage Reservoirs. — In regions — particularly the Western States — where the supply of water from the primary source is not constant throughout the year, means must be resorted to for furnishing the deficit from a secondary source, or reservoir, during the season of low water.

Storage reservoirs are of two kinds — natural and artificial. Natural reservoirs are found principally in the West, east of the Rocky Mountains. These natural basins, or depressions, collect the water run off in the wet season from the surrounding watershed, and retain it in ponds until it is partly or wholly lost by evaporation. Such natural basins are frequently utilized for storage reservoirs by conducting water into them from adjacent streams, and providing them with outlets, by means of which they are connected with the primary source of supply. Moreover, they are frequently found at elevations sufficiently high to enable high heads to be secured by leading the pipe or conduit line down the gradient into the valley or canyon, wherein is located the power plant.

Artificial reservoirs are generally formed by erecting a dam across a valley at a point where the topography of the country is such as to obviate any loss of water into another

watershed, or by leakage from the dam. The reservoir should also be formed sufficiently high up in the valley to permit the water to flow freely to the place of utilization, or not infrequently to furnish the desired head of water at this point.

It is quite desirable that the valley be narrow and the surrounding hills be steep at the point where the dam is located, so as to prevent both expensive construction and shallow water. However, a basin or valley with slight longitudinal slope will afford a given amount of storage with less height of dam than one with a precipitous channel.

The location of a reservoir, or system of reservoirs, for supplying a hydraulic plant depends on the particular conditions which must be met, such as the quantity of water which the auxiliary source of supply must furnish in the drought season; the length of the low season; the area of the supplying watershed, and the quantity of water which can be impounded in the rainy season.

Aside from the water-impounding area afforded by the contour of the country, the capacity of storage reservoirs depends on the annual precipitation and the climatic conditions in the particular region; the size of the watershed drained, and the losses from leakage and evaporation. The latter loss generally ranges from 8 per cent to 12 per cent of the consumption. In dry, arid regions of the West, the loss by evaporation amounts to 75 per cent or more of the consumption per annum.

Waste Weirs or Spillways. — Waste weirs find application in discharging surplus water from reservoirs or dams. They are usually constructed in the sides of a reservoir, and have no end contractions. When a waste weir is made with a narrow crest and a vertical front, the dis-

charging stream of water will have air beneath it, and the quantity of water discharged is, by Francis's formula,

$$q = 3.33\ bH^{\frac{3}{2}},$$

where b represents the length of the crest, and H the head measured at a definite distance back of the crest. The equation is modified by a wide crest and sloping approach, the discharge in such cases being slightly less. For a crest with inclined approach and about three feet wide, the formula of Francis becomes

$$q = 3.01\ bH^{1.53}.$$

Since it is extremely difficult to determine the exact discharge which is to pass over a waste weir, the accurate determination of its length is unimportant; but a large factor of safety should be allowed in order to obviate the dangers from exceptional floods.

When, as in the case of dams, the water flows over an apron of timber or masonry, the inclination of the material, as well as the inclination of the approach to the crest, changes the form of the equation, which then becomes

$$q = \tfrac{2}{3}\sqrt{2g}\ bH^{\frac{3}{2}} = mbH^{\frac{3}{2}},$$

in which H is the head due to velocity of approach, and m is a constant, the value of which ranges between 2.5 to 4.3.

Several forms of waste weirs exist: (1) Waste weirs excavated in natural soil at one or both ends of the dam. (This type is not safe unless the foundation is of rock.) (2) Spillways channeled through some low point in the dividing ridge and the water conducted to another valley. (3) A portion of the dam (if of masonry) is designed as a spillway, and is located at about the axis of the valley.

When spillways of the latter type are used, their construction should be so substantial that the strains of overflow from floods will not affect them.

The tops of spillways should also be so designed as to resist the blows of, and pass over, logs, ice, or débris, brought down by floods.

Loss of Head in Pipe Lines. —The principal sources of loss which occur in pipe lines are due to (1) Friction; (2) contraction of the area; (3) constriction of the orifice; (4) curvature.

The first and principal loss is caused by the resistance to flow offered by the interior surface of the pipe. In very long pipes it becomes quite prominent, so that the discharge may be but a small percentage of that due to the head.

The loss of head by friction may be ascertained for any particular case by measurement of the head h, the area a of the cross-section of the pipe, and the discharge q per second.

Five approximate laws govern the friction loss in pipe lines: (1) The loss by friction is proportional to the length of the pipe. (2) It varies nearly as the square of the velocity. (3) It decreases as the diameter of the pipe increases. (4) It increases with the roughness of the inside surface. (5) It is independent of the pressure of the water.

Or stated in the form of an equation:

$$h_f = c\frac{l}{d} \cdot \frac{v^2}{2g},$$

where c is the coefficient of friction, l the length of the pipe in feet, d its diameter in the same units, and v the

velocity of flow. The equation is but an empirical one since the theoretical expression for h_f has not as yet been determined.

The friction factor is governed by the character of the interior surface of the pipe, diminishing with smoothness of surface. A value commonly employed is 0.02.

While our knowledge of the internal frictional resistances of flowing water is still in a very unsettled state, it appears that the energy transformed by friction into heat is lost in two ways: by direct friction along the inside surface, and by impact caused by the varying motion of the particles of water.

Loss of head, due to the contraction of the cross-section of a pipe, also causes a contraction of the water stream, and its tendency to expand to fill the diminished section causes loss in head.

In the case of a gradual contraction in the cross-section of a pipe, which is the more common one, the loss in head can be determined for any definite velocity by noting the difference in height between two pressure columns, one of which is inserted just above the point where the cross-section changes, and the other, slightly below the point where the contracted section commences.

Having determined the values for the velocities v_1 and v_2, and the heads h_1 and h_2, in the respective cross-sections, the loss in head, occasioned by a contraction of cross-section, becomes

$$h' = \frac{(v_1 - v_2)^2}{2g} + h_1 - h_2.$$

If there is no subsequent increase of cross-section, the loss of head from this cause is not appreciable, since it is due to loss of velocity caused by abrupt expansion.

Loss of head in a pipe line may also be caused by a sudden constriction of the orifice of the pipe. It is explained by the fact that the particles of water, as they approach the orifice, move in converging directions; hence such contraction of the stream causes only the inner corner of the orifice to be touched by the water in its outward passage.

When a pipe line is laid on a curve the water flow is changed in direction, which causes an increase of pressure in the direction of the radius of the curve and away from its center. The increase of pressure sets up eddying movements in the water, causing impacts against the wall of the pipe. Such impacts dissipate some of the energy of the head by transforming it into heat. It is obvious that the loss of head h_c, caused by a curve in a pipe line, increases with its length. It is also larger for small pipes than for large ones.

The loss of head, caused by a curve in a pipe line, is expressed by the following equation,

$$h_c = f_c \frac{l}{d} \cdot \frac{v_2}{2g},$$

in which f_c is a number termed the curve factor, the value of which depends upon the ratio of the radius of the pipe to its diameter; l is the length of the curve; d the diameter of the pipe, and v the mean velocity of flow. Representing by R the radius of the circle in which the center line of the pipe is laid, as the ratio $\frac{R}{d}$ decreases, the value of f_c increases.

Owing to a lack of sufficient experimental data to determine accurate values for the curve factor f_c, the equation

can only be considered as a rough guide. For cast iron pipe, Messrs. Hubbell and Frenkell determined the following values of the curve factor for 30-inch pipe laid with a curve of 90 degrees:

$\frac{R}{d} =$	24	16	10	6	4	2.4
$f_c =$	0.036	0.037	0.047	0.060	0.062	0.072.

When there are several bends or curves in a pipe line, the value of $f_c \frac{l}{d}$ is computed for each curve; and the sum of these values is taken in order to find the total loss of head due to the curvatures.

The equation then becomes

$$h_c = k \cdot \frac{v^2}{2g},$$

in which k represents the sum of these values for all the curves.

The loss in head caused by curves in a pipe or flume line is generally small compared with that lost in friction, as the curves are made as few and as slight as possible.

Mean Velocity of Flow in Pipes. — Assuming that the pipe is running full, the formula for mean velocity of flow can be deduced from the factors which have been thus far stated. Let h be the maximum head, $\frac{v^2}{2g}$ the effective velocity head of the issuing stream, and $h - \frac{v^2}{2g}$ the lost head. The lost head is equal to the sum of its component parts, which may be called $h' + h_f + h_c$.

Loss of Head in Pipe by Friction

The following tables show the loss of head by friction in each 100 feet in length of different diameters of pipe, when discharging the following quantities of water per minute:

INSIDE DIAMETER OF PIPE IN INCHES.

	13		14		15		16		18		20	
Vel. in ft. per sec.	Loss of head in feet.	Cubic feet per min.	Loss of head in feet.	Cubic feet per min.	Loss of head in feet.	Cubic feet per min.	Loss of head in feet.	Cubic feet per min.	Loss of head in feet.	Cubic feet per min.	Loss of head in feet.	Cubic feet per min.
2.0	.183	110.	.169	128.	.158	147.	147	167.	.132	212.	.119	262.
2.2	.216	121.	.200	141.	.187	162.	175	184.	.156	233.	.140	288.
2.4	.252	133.	.234	154.	.218	176.	.205	201.	.182	254.	.164	314.
2.6	.290	144.	.270	167.	.252	191.	.236	218.	.210	275	.189	340.
2.8	.332	156.	.308	179	.288	206.	.270	234.	.240	297.	.216	366.
3.0	.375	166.	.349	192.	.325	221.	.306	251.	.271	318.	.245	393.
3.2	.422	177.	.392	205.	.366	235.	.343	268.	.305	339.	.275	419.
3.4	.471	188.	.438	218.	.408	250.	.383	284.	.339	360.	.306	445.
3.6	.522	199	.485	231.	.452	265.	.425	301.	.377	382.	.339	471.
3.8	.576	210.	.535	243.	.499	280.	.468	318.	.416	403.	.374	497.
4.0	.632	221.	.587	256.	.548	294.	.513	335.	.456	424.	.410	523.
4.2	.691	232.	.641	269.	.598	309.	.561	352.	.499	445.	.449	550.
4.4	.751	243.	.698	282.	.651	324.	.611	368.	.542	466.	.488	576.
4.6	.815	254.	.757	295.	.707	339.	.662	385.	.588	488.	.529	602.
4.8	.881	265.	.818	308.	.763	353.	.715	402.	.636	509	.572	628.
5.0	.949	276.	.881	321.	.822	368.	.770	419.	.685	530.	.617	654.
5.2	1.020	287.	.947	333.	.883	383.	.828	435.	.736	551.	.662	680.
5.4	1.092	298.	1.014	346.	.947	397.	.888	452.	.788	572.	.710	707.
5.6	1.167	309.	1.083	359.	1.011	412.	.949	469.	.843	594.	.758	733.
5.8	1.245	321.	1.155	372.	1.078	427.	1.011	486.	.899	615.	.809	759.
6.0	1.325	332.	1.229	385.	1.148	442.	1.076	502.	.957	636	.861	785.
7.0	1.75	387.	1.630	449.	1.520	515.	1.430	586.	1.270	742.	1.143	916.

INSIDE DIAMETER OF PIPE IN INCHES.

	22		24		26		28		30		36	
Vel. in ft. per sec.	Loss of head in feet.	Cubic feet per min.	Loss of head in feet.	Cubic feet per min.	Loss of head in feet.	Cubic feet per min.	Loss of head in feet.	Cubic feet per min.	Loss of head in feet.	Cubic feet per min.	Loss of head in feet.	Cubic feet per min.
2.0	.108	316.	.098	377.	.091	442.	084	513.	.079	589.	.066	848.
2.2	.127	348.	.116	414.	.108	486.	.099	564	.093	648.	.078	933.
2.4	.149	380.	.136	452.	.126	531.	.116	616.	.109	707.	.091	1018.
2.6	.171	412.	.157	490.	.145	575.	.134	667.	.126	766.	.104	1100.
2.8	.195	443.	.180	528.	.165	619.	.153	718.	.144	824.	.119	1188.
3 0	.222	475.	.204	565.	.188	663.	.174	770.	.163	883.	.135	1273.
3.2	.249	507.	.229	603.	.211	708.	.195	821.	.182	942.	.152	1357.
3.4	.278	538.	.255	641.	.235	752.	.218	872.	.204	1001.	.169	1442.
3.6	.308	570.	.283	678.	.261	796.	.242	923.	.226	1060.	.188	1527.
3.8	.340	601.	.312	716.	.288	840.	.267	974.	.249	1119.	.207	1612.
4.0	.373	633.	.342	754.	.315	885.	.293	1026.	.273	1178.	.228	1697.
4 2	.408	665.	.374	791.	.345	929	.320	1077.	.299	1237.	.249	1782.
4.4	.444	697.	.407	829.	.375	973.	.348	1129.	.325	1296.	.271	1866.
4.6	.482	728.	.441	867.	.407	1017	.378	1180.	.353	1355.	.294	1951.
4.8	.521	760.	.476	905.	.440	1062.	.409	1231.	.381	1414.	.318	2036.
5.0	.561	792.	.513	942.	.474	1106.	.440	1283.	.411	1472.	.342	2121.
5.2	.602	823.	.552	980.	.510	1150.	.473	1334.	.441	1531.	.368	2206.
5 4	.645	855.	.591	1018.	.546	1194.	.507	1385.	.473	1590.	.394	2291.
5.6	.690	887.	.632	1055.	.583	1239.	.542	1437.	.506	1649.	.421	2376.
5.8	.735	918.	.674	1093.	.622	1283.	.578	1488.	.540	1708.	.450	2460.
6.0	782	950.	.717	1131.	.662	1327.	.615	1539.	.574	1767.	.479	2545.
7.0	1.040	1109.	.953	1319.	.879	1548.	.817	1796.	.762	2061.	.636	2968.

The following formula, deduced by Wm. Cox, gives practically the same results as the above table and will be found useful in many instances. $F = \frac{L}{1000\,D}(4\,V^2 + 5\,V\text{-}2)$. Where F = friction head, L = length of pipe in feet; D = diameter of pipe in inches; V = velocity in feet per second.

Table I

Substituting the values of h', h_f, and h_c, from the previous paragraphs,

$$h = \frac{v^2}{2g} + m\frac{v^2}{2g} + c\frac{l}{d} \cdot \frac{v^2}{2g} + n\frac{v^2}{2g},$$

where $m\frac{v^2}{2g}$ is the loss of head at the entrance (negligible for long pipes); $c\frac{l}{d} \cdot \frac{v^2}{2g}$, the loss by friction, and $n\frac{v^2}{2g}$, the loss due to curvature.

Solving for v, the equation becomes

$$V = \sqrt{\frac{2gh}{1 + m + C\frac{l}{d} + n}},$$

which is applicable satisfactorily to pipes of moderate length.

Determination of Discharge from Pipes. — The discharge per second from any pipe of a given diameter is found by multiplying the area of its cross-section by the velocity of discharge, which, stated as a formula, is

$$q = \frac{\pi}{4} d^2 V.$$

Determination of the Diameter of Pipe to Discharge a Given Quantity of Water. — Let d represent the diameter, l the required length of the pipe line, q the quantity of water to be discharged, h the head, and f the coefficient of friction (0.02).

Neglecting the influence of curvature, an equation for diameter is

$$d = 0.479 \left[(1.5d + fl) \frac{q^2}{h} \right]^{\frac{1}{5}},$$

in which the values of h, l, and d are taken in feet, and that

of q in cubic feet per second. In applying this formula two computations are generally made. In the first calculation, d in the right-hand side is disregarded and a rough value for the diameter is calculated. Then determining the velocity from the equation

$$v = \frac{q}{\frac{\pi d^2}{4}}$$

the friction coefficient for this velocity is looked up in a table of coefficients. A second calculation of d is then made, using in the right-hand side of the equation the rough value of d first derived.

To arrive at the value of d with a fair degree of accuracy, several computations are generally made, using each time the approximate value of d obtained by the preceding computation.

Long Pipes. — A pipe is said to be long when its length is approximately 4,000 times its diameter, or more. In the West, particularly in California, the pipe or flume lines which conduct the impounded water to the hydraulic machines range in length from a few hundred feet up to seven miles or more, and it is with this class of pipes that we are principally concerned.

In long pipes the friction loss predominates, the velocity head being usually small. The expression for velocity, when a long pipe is running full, is

$$v = \sqrt{\frac{2gdh}{cl}} = 8.02 \sqrt{\frac{dh}{cl}};$$

in which the letters have the significance assigned in previous paragraphs.

The discharge per second through a long pipe is given by the expression

$$q = \frac{\pi}{d} d^2 v = 6.30 \sqrt{\frac{d^5 h}{cl}}.$$

Maximum Energy Transmitted by a Water Pipe. —

Let Q = total cubic feet of water.
D = diameter of the pipe.
h = total head.
l = length.

The relation between these quantities becomes

$$Q = 38.5\ D^{\frac{5}{2}} \sqrt{\frac{h}{l}}.$$

A cubic foot of water falling through a distance of one foot develops

$$\frac{62.5 \times 60}{33{,}000} = 0.1135 \text{ horse-power.}$$

Then $$\text{H. P.} = 0.1135\ Q\ H,$$

where H equals the distance of fall in feet and Q = quantity of water in cubic feet per second. Hence if h_f is the loss of head due to friction, the horse-power delivered at any distance L feet away is

$$\text{H. P.} = 0.1135\ Q\ (H - h_f).$$

By substituting the value of Q the relation becomes

$$\text{H. P.} = 0.1135 \times 38.5 \cdot D^{\frac{5}{2}} \sqrt{\frac{h}{L}}\ (H - h_f).$$

Calling the value of h_f equal to kH (where k equals

the sum of all the curve factors) we get by substituting and reducing

$$\text{H. P.} = 4.37 \sqrt{\frac{kH^3 D^5}{L}} \cdot (1 - s),$$

and

$$L = \frac{19.1\, kH^3 D^5 (1 - s)}{\text{H. P.}^2}.$$

The first formula gives the horse-power that can be transmitted for any definite fraction of the head lost in friction; and the second, the length of pipe which will transmit a given amount of power with a given loss.

Loss of head is proportional to V^2 and loss of power to V, hence the maximum power is transmitted when one-third of the head is dissipated in friction.

Mean Velocity of Flow in Canals and Conduits. — The general empirical formula of Chezy for the mean velocity of flow in streams is also applicable to conduits and canals, and, with some modifications, to all forms of channels. For a circular conduit running full or half full, the hydraulic radius $r = \frac{1}{4}d$; hence the mean velocity is

$$v = c\sqrt{rs} = c \,.\, \tfrac{1}{2}\sqrt{ds},$$

where c is the friction coefficient, the value of which depends upon the roughness of the conduit and its curvature, and s is the slope.

The discharge from the same kind of channel is then given by the equation

$$q = av = c \,.\, \tfrac{1}{2}a\sqrt{ds},$$

in which a is either one-half of the area of the cross-section, or the entire circular cross-section.

For a rectangular conduit, the velocity and discharge are given by the equations

$$v = c\sqrt{rs} \quad \text{and} \quad q = av = c \cdot a\sqrt{rs},$$

the values of c being taken from a table of coefficients for circular conduits.

In case the depth of water is greater or less than one-half the diameter of the pipe, the value of c increases with r. It also increases greatly with the degree of roughness.

The empirical formula of Kutter (derived from the experiments conducted by Ganguillet and Kutter in 1869) is now universally employed for determining the value of c in the Chezy formula, since it is applicable to all kinds of surfaces. In fact, it may be said in general, that no design for channels is now made without its employment in the preliminary investigations. The formula of Kutter for c is

$$c = \frac{\frac{1.811}{n} + 41.65 + \frac{0.00281}{s}}{1 + \frac{n}{\sqrt{r}}\left(41.65 + \frac{0.00281}{s}\right)},$$

where r is expressed in feet, and v in feet per second; n is an abstract number of a value depending upon the character of the surface.

In Kutter's formula the value of c is expressed in terms of the hydraulic radius r, slope s, and the degree of roughness of surface.

The Contruction of Flumes.— Flumes are frequently employed for conveying water to hydro-electric plants, but are not considered as economical as pipe systems or conduits, since the loss in leakage is greater; and they are

also more liable to damage or destruction from snow-storms, wind, and decay. In mountainous regions, however, where timber is abundant, and the cost of transporting the pipe system prohibitive, their use may be more advantageous than other forms of water-conducting systems. A flume can be made much smaller than a canal on account of the high permissible velocity of water in it, which is usually about 6 or 8 feet per second. Flumes also offer much less resistance to the flow of water than canals, which give a smaller loss of head for the same capacity.

Flumes are generally constructed in rectangular form of durable timber, and are supported either on trestles, or stone or concrete blocks. When a flume system is supported on level benches, cut in the hillside or soil, the flume is termed a bench flume. Bench flumes are supported on concrete brick or solid stone. In crossing a rough section of country, or a valley or divide, flumes are supported on trestles.

The timber used in the construction of flumes should be of a variety which does not easily decay, and which is also plentiful in the neighborhood. When a flume line is laid near the base of a hillside or mountain, the bed on which it rests should be excavated in the side of the elevation, and the flume laid very close to the bank, as a precaution against damage from snow or wind storms. In exposed places, flumes are covered with planks and timber from two to six inches in thickness, as a protection against rolling bowlders and landslides.

In California, where flumes are extensively used as water-conducting systems for hydro-electric plants, the flume boxes are generally constructed of clear, surfaced redwood, placed in position longitudinally to the flow of water. The

trestle caps, stringers, and yokes are usually made of Oregon pine.

Fig. 12 shows a type of California flume constructed of the materials as stated above.

Flumes are braced at intervals of several feet by diagonal scantlings nailed to horizontal timbers or sills, fastened to the bottom. The construction employed when the loss in leakage is desired to be kept as small as possible, consists of a double thickness of planking, the inner one being sometimes coated with tar or asphaltum to prevent any seepage of water, and also to prolong its life. The length of life of a flume is greatly prolonged by creosoting the timber, but the construction is rendered much more expensive thereby.

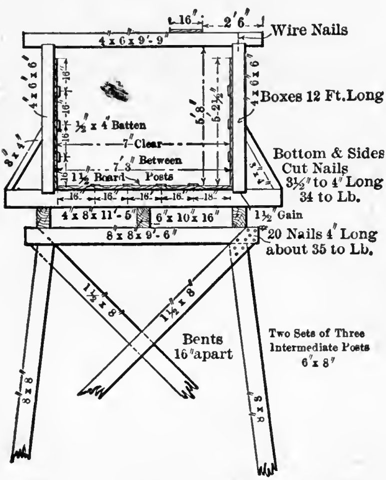


Fig. 12. Type of Flume used in Some California Plants

A type of flume used principally on the Pacific coast is known as the stave and binder flume. In this type the bottom is constructed like the lower half of wood stave pipe, but vertical sides are used instead of the closed top. A binding rod is passed around the flume, its ends passing through the two ends of a cross-head, and provided with nuts by means of which the staves are forced together. Flumes of this shape are supported on T-shaped frames made of T-iron, and resting on wooden bolsters, spaced

UNIVERSITY OF CALIFORNIA

about 8 feet apart; each frame resting on concrete blocks. Trestles for supporting flume lines are made of either wood or steel, with footings constructed of a cement con-

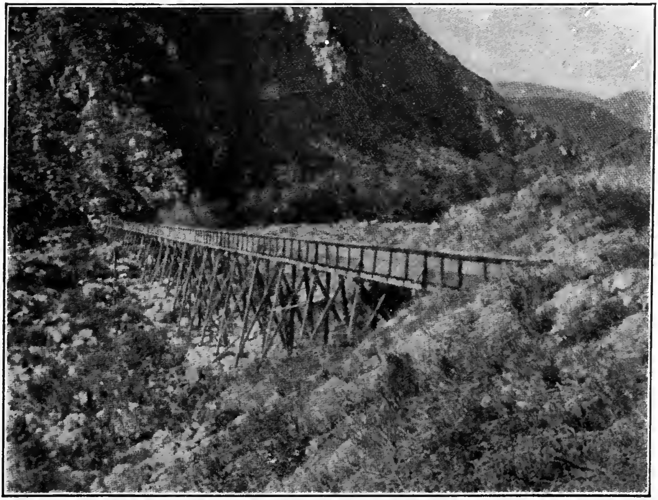


Fig. 13. Flume Supported on Trestle

crete. Fig. 13 shows a flume line carried on a wooden trestle.

Waste flumes are designed to carry away the overflow from forebays, and are similar in design to conducting flumes.

When a flume or water-conducting channel runs through a forest, means must be adopted to prevent leaves and twigs which fall in the water from entering the connecting pipe line or penstock. Figs. 14 and 15 illustrate a device employed in the flume line of the Mill Creek Plant of the California Edison Company, to free the water of such

matter before it reaches the connecting pipe line. It comprises an endless wire screen, wound over two drums, the lower end of the screen being immersed in the water, thus catching and removing the floating matter from the water, and depositing it in a mass underneath the upper end. Movement of the screen drum is effected by means of a

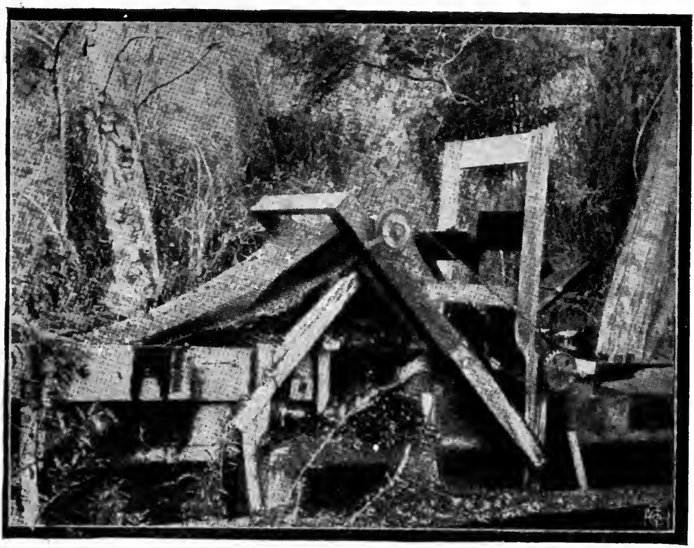


Fig. 14. Device for Removing Leaves and Twigs from Flume Lines

sprocket chain actuated by an undershot wheel, which is operated by the current in the flume.

Precautions are also adopted to prevent the sand which enters the flume line from the supplying stream, from getting into the connecting line, where it would quickly abrade the metal and cause serious damage to the nozzles and buckets of the wheel.

Circumferential Pressure in Pipes. —

Let i = intensity of strain,
r = radius of pipe,
p = pressure-head,
t = thickness of shell.

Then
$$i = \frac{p\,r}{t}.$$

For stresses in riveted steel pipe:

Let i = intensity of strain,
e = modulus of elasticity,
t = change of temperature,
k = coefficient of expansion.

Then
$$i = e\,t\,k.$$

The Construction of Pipe Lines. — The method of conveying water to hydraulic machines by means of pipe lines has become almost universal practice on the Pacific coast, and in mountainous sections of the West. The material used in the construction of pipe lines is either wood, cast iron, wrought iron, or steel, the latter being generally used in the riveted form.

The use of wood stave pipe as a conveying medium for water is quite general in some sections of the West. It is constructed of redwood, fir, cypress, pine, or other durable woods with wooden tongue-butt joints, the sections being bound with steel bands, and held together with clips or shoes made of cast iron. The pressure which a wooden stave pipe can safely withstand depends upon the hardness of the saturated wood — a working head of 200 feet having been shown by experience to be a safe practical limit in the case of redwood and Douglass fir.

Among the advantages claimed for wooden stave pipe are: (1) Greater discharging capacity than metal pipe of the same diameter, due to the fact that the friction factor does not increase with age — *i.e.*, they do not become rougher with age. (2) The materials for constructing a stave pipe can be easily transported to the region through

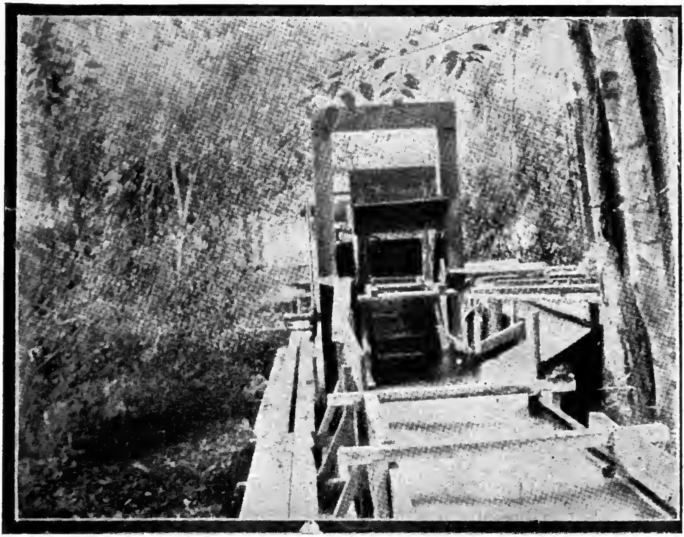


Fig. 15. Undershot Wheel which Actuates Device Shown in Fig. 14

which a pipe line must be laid, and the pipe system constructed on the site. This is an important advantage when the water-conducting medium traverses a rough and mountainous country where it would be very difficult or impossible to transport heavy metal pipe. (3) It is cheaper than metal pipe. The cost of a 30 inch redwood pipe laid and buried was $3.90 per foot for 200 feet head. *

* Adams, Transactions American Society Civil Engineers, 1898, p. 676.

The disadvantages of stave pipe are: (1) It is shorter lived than metal pipe. It is manifest that changes of temperature and wind will cause a steady movement back and forth of the limit of saturation within the staves, thus leaving the outer skin of the wood in a condition which invites decay. Adams claims, however, that there are some stave pipe lines in New England that are constructed of pine and have lasted from 20 to 40 years. Evidently, redwood pipe lines should last much longer. (2) It is

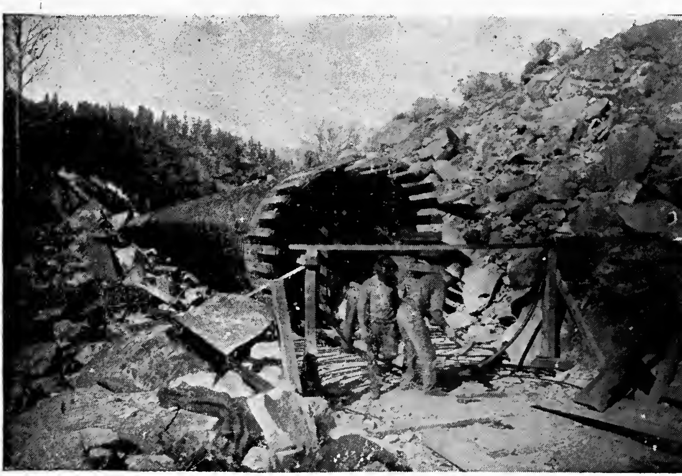


Fig. 16. Construction of Stave Pipe Line

subject to attack from insects, rodents, etc. (3) Evaporation losses from wood pipe are considerable.

To prevent evaporation losses it has been proposed to put a protective coating of asphalt or paint on the outside of the pipe.

Fig. 16 shows the construction of a Wheeler continuous stave pipe, made by the National Wood Pipe Co., of Los

Angeles, and Fig. 17 shows a completed pipe line. Stave pipe is used in sizes ranging from a few inches up to 10 feet in diameter.

When iron pipe is used, cast iron is preferable to wrought iron, since it rusts materially less than wrought iron, and its life is practically unlimited. It is also non-

Fig. 17. Completed Wooden Pipe Line

collapsible and capable of withstanding as high hydrostatic pressures as wrought iron.

In some Western transmission practice the pipe lines are constructed of steel or wrought iron in one part of their length, and cast iron in the other; and are graduated in thickness, being of heaviest metal near the receivers.

The joints used on continuous metal pipe are usually of the flange type, the sections being bolted together. Fig. 18*a* shows a type of joint used on the cast iron pipe line of a

California transmission company. A groove extends round the flange, into which is forced a circular rubber gasket of a slightly smaller diameter than the groove in the flange. It is placed in the groove, and when the rivets are inserted and the flanges drawn together, the sections of pipe are united metal to metal. Water pressure tends to force the gasket more firmly into the recess of the flange and insures absolute water tightness.

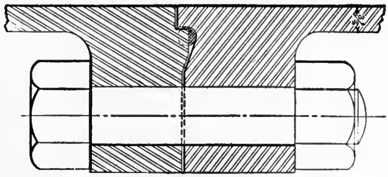


Fig. 18a. A Type of Joint for High-head Pipe Lines

Iron pipe for conveying water to hydro-electric plants is rarely used in sizes larger than 3 or 4 feet in diameter.

Riveted pipe is more widely used for a water-conducting medium than any other kind of metal pipe. It is made from iron or sheet steel plates of the thickness required to withstand the pressure, these being rolled to the desired diameter. The plates or sheets are held together by a double or triple row of rivets along the longitudinal seam, and a single row of rivets along the circular seams. As a protection against corrosion and in order to decrease the frictional resistance, each section of pipe is immersed in a vat of hot asphaltum, which gives it a smooth finish on the interior.

The sections of riveted pipe are joined together either by means of slip joints, if the head of water on the line does not exceed 350 feet; or by means of collar and sleeve joints, when the head is not much over 750 feet; or by flanged joints, when the head is considerably above 750 feet.

On most riveted pipe, joints are made by means of a

single row of rivets commonly called "round seams." In this style of riveting, holes are accurately punched by a multiple punching machine, and the joints of the sections riveted with cold rivets on light gauges, and hot rivets on the heavier gauges. The pipe is then chipped and caulked to insure a water-tight joint, metal to metal, around the joint. At points where the lap in the joint occurs, the

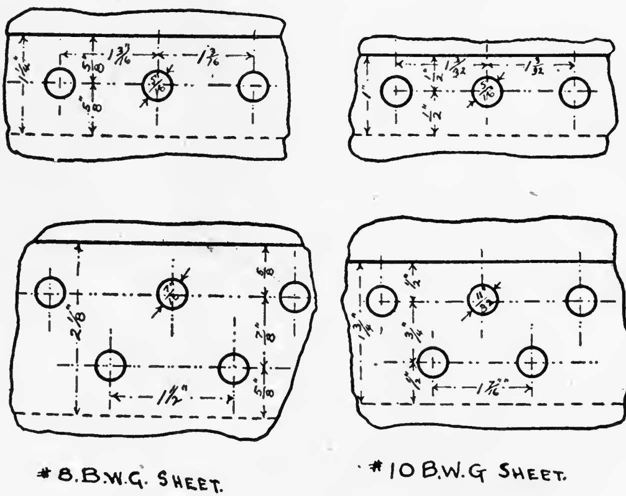


Fig. 18b Fig. 18c

Size and Spacing of Rivets on Pipe Lines

metal of the overlapping joint is likewise chipped and caulked. Finally, the inside and outside of the joint are painted with asphaltum as a protection against corrosion by the action of water and chemicals in the soil.

Pipe ranging from 24 inches in diameter upward is generally continuous-riveted, and varies in thickness from No. 14 to 0000 B. W. G. Lap welded pipe for heavier gauges is also quite common.

On lighter gauge pipes "bump" joints are generally

used. These are constructed by expanding one end of a section enough to permit the other near end of the next section to enter it. Then holes are punched through both the sections of pipe, at the ends to be joined together, and the riveting done by means of hot rivets in a similar manner to that employed on round seams.

Usually, on very light gauges of pipe of the bump joint

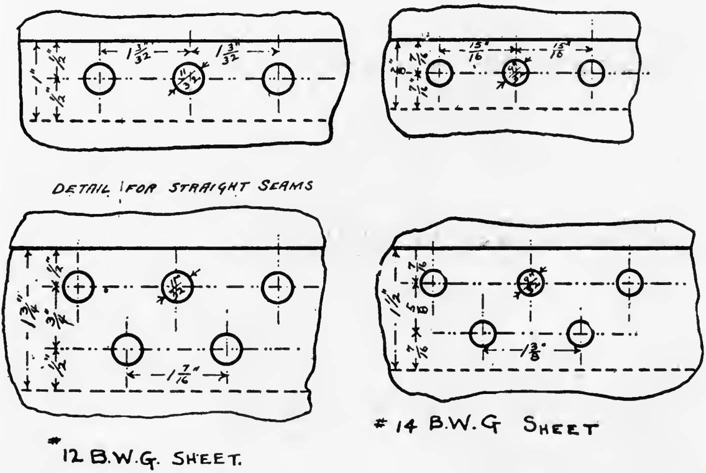


Fig. 18d

Fig. 18e

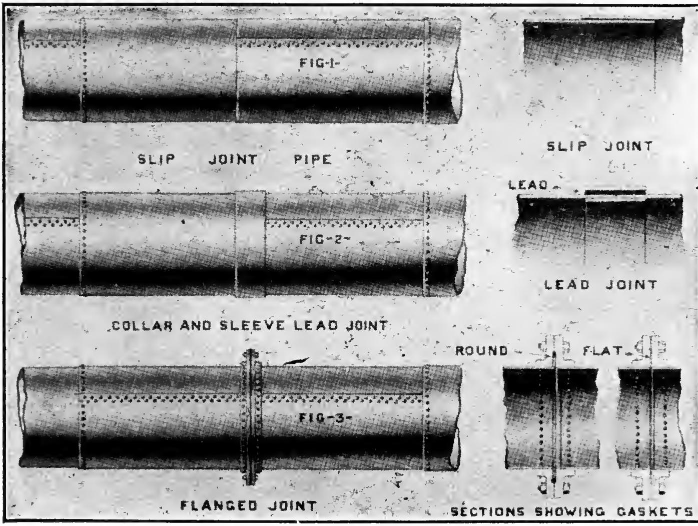
Size and Spacing of Rivets on Pipe Lines

type, a single row of rivets is used on the joint. On pipes of from one-half to three-fourths inch diameter, double rivets are generally used, and the rivets staggered as on straight seams on riveted pipe. Figs. 18*b*, 18*c*, 18*d*, and 18*e*, show the size and spacing of rivets used in many Western pipe lines.

Figs. 19, 20, and 21 show the three methods of connection employed on riveted pipe, and also illustrate riveted steel pipe made by the Pelton Wheel Company. Riveted

section pipe has been satisfactorily employed to convey water under heads up to 2,000 feet.

The material used in some pipe lines is open hearth, box-annealed steel of a tensile strength, ranging from 40,000 to 60,000 pounds per square inch, and with riveted joints. The preference for steel over iron is to some extent a



Figs. 19, 20, 21. Methods of Connecting Riveted Pipe

matter of cost. Pipes are calculated to resist a certain pressure, and the greater tensile strength of steel is an important factor; in order to resist the same pressure an iron pipe of much greater weight would be required.

On the other hand, steel pipe is much more liable to be damaged by electrolytic action when laid on alkali soils. Under such conditions iron and carbon form the two ele-

ments, differing in the electrochemical series, while alkali is the electrolyte.

With iron pipe very little electrolytic action ensues, since iron contains very little carbon.

Pipe lines for conveying water to hydro-electric plants are generally laid on the surface of the ground, and when the gradient is steep they are securely anchored by embedding them in cement blocks spaced 10 or 15 feet apart. Fig. 22 shows the pipe line and method of anchoring adopted by the Bay Counties Power Company of California.

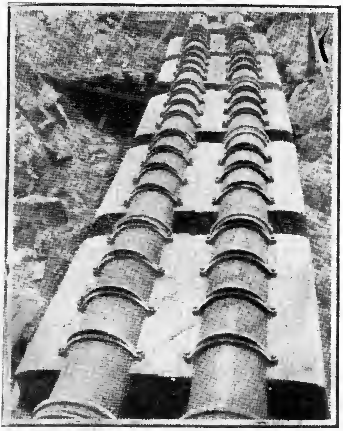


Fig. 22. Method of Anchoring Pipe Lines on Steep Grades

In some cases pipe systems are laid in trenches from 3 to 6 feet deep and back-filled with earth and rock. At various points along the line heavy anchors of concrete are placed, extending all around the pipe. These anchorages are generally dovetailed into the solid rock in the sides and bottom of the trench, and hold the pipe rigidly.

All curves on pipe lines should be made with a long radius to reduce the loss of head. At points near the receiver, and where inverted siphons are used, blow-offs, air valves, or other safety devices should be installed in order to prevent accidents from bubbles, water hammer, and vacuum.

A standpipe for the escape of air bubbles is sometimes

Table of Riveted Hydraulic Pipe

Showing price and weight, with safe head for various sizes of double riveted pipe.

(Revised)

Diameter of pipe in inches	Thickness of material U. S. standard gauge	Equivalent thickness in inches.	Head in feet pipe will safely stand.	Weight per lineal foot in pounds.	Price per foot.
3	18	.05	810	2.25	$0.20
4	18	.05	607	3.00	.25
4	16	.062	760	3.75	.35
5	18	.05	485	3.75	.30
5	16	.062	605	4.50	.45
5	14	.078	757	5.75	.50
6	18	.05	405	4.25	.44
6	16	.062	505	5.25	.50
6	14	.078	630	6.50	.56
7	18	05	346	4.75	.50
7	16	.062	433	6.00	.56
7	14	.078	540	7.50	.63
8	16	.062	378	7.00	.65
8	14	.078	472	8.75	.75
8	12	.109	660	12.00	.94
9	16	.062	336	7.50	.69
9	14	.078	420	9.25	.88
9	12	.109	587	12.75	1.06
10	16	.062	307	8.25	.72
10	14	.078	378	10.25	.82
10	12	.109	530	14.25	1.00
10	11	.125	607	16 25	1.25
10	10	.14	680	18.25	1.50
11	16	.062	275	9.00	.75
11	14	.078	344	11 00	.94
11	12	.109	480	15.25	1.25
11	11	.125	553	17.50	1.44
11	10	.14	617	19.50	1.62
12	16	.062	252	10.00	.82
12	14	.078	316	12.25	1.00
12	12	.109	442	17.00	1.38
12	11	.125	506	19.50	1.50
12	10	.14	567	21.75	1.69
13	16	.062	233	10.50	.90
13	14	.078	291	13.00	1.12
13	12	.109	407	18.00	1.50
13	11	.125	467	20.50	1.65
13	10	.14	522	23.00	1.80
14	16	.062	216	11.25	.98
14	14	.078	271	14.00	1.17
14	12	.109	878	19.50	1.57
14	11	.125	433	22.25	1.72
14	10	.14	485	25.00	1.95
15	16	.062	202	11.75	.96
15	14	.078	252	14.75	1.28
15	12	.109	352	20.50	1.75
15	11	.125	405	23.25	1.95
15	10	.14	453	26.00	2.10
16	16	.062	190	13.00	1.05
16	14	.078	237	16.00	1.20
16	12	.109	332	22.25	1.70
16	11	.125	379	24.50	1.85
16	10	14	425	28.50	2.00
18	16	.062	168	14.75	1.20
18	14	.078	210	18.50	1.40

Diameter of pipe in inches.	Thickness of material U. S. standard gauge.	Equivalent thickness in inches.	Head in feet pipe will safely stand.	Weight per lineal foot in pounds.	Price per foot.
18	12	.109	295	25.25	$1.90
18	11	.125	337	29.00	2.10
18	10	.14	378	32.50	2.40
18	8	.171	460	40.00	3.00
20	16	.062	151	16.00	1.26
20	14	.078	189	19.75	1 54
20	12	.109	265	27.50	2.10
20	11	.125	304	31.50	2.25
20	10	.14	340	35.00	2.50
20	8	.171	415	45.50	3.40
22	16	.062	138	17.75	1.40
22	14	.078	172	22.00	1.70
22	12	109	240	30.50	2.25
22	11	.125	276	34.50	2.40
22	10	.14	309	39.00	2.80
22	8	171	376	50.00	3.75
24	14	.078	158	23.75	1.80
24	12	.109	220	32.00	2.35
24	11	.125	253	37.50	2.70
24	10	.14	283	42.00	2.95
24	8	.171	346	50.00	3.50
24	6	.20	405	59.00	4.30
26	14	.078	145	25.50	2.00
26	12	.109	203	35.50	2.59
26	11	.125	233	39.50	2.87
26	10	.14	261	44.25	3.10
26	8	.171	319	54.00	3.85
26	6	.20	373	64.00	4.75
28	14	.078	135	27.25	2.12
28	12	.109	188	38.00	2.75
28	11	.125	216	42.25	3.00
28	10	.14	242	47.50	3.20
28	8	.171	295	58.00	4.15
28	6.	.20	346	69 00	5.00
30	12	.109	176	39.50	2.90
30	11	.125	202	45.00	3.15
30	10	.14	226	50.50	3 50
30	8	.171	276	61.75	4.30
30	6	.20	323	73.00	5.25
30	1/4	.25	404	90 00	6.50
36	11	.125	168	54.00	3.80
36	10	.14	189	60.50	4.30
36	3/16	.187	252	81.00	5.75
36	1/4	.25	337	109.00	7.60
36	5/16	.312	420	135.00	9.50
40	10	.14	170	67.50	4.75
40	3/16	.187	226	90.00	6 40
40	1/4	.25	303	120 00	8.40
40	5/16	.312	378	150.00	10.50
40	3/8	.375	455	180.00	12.00
42	10	.14	162	71.00	5.05
42	3/16	.187	216	94.50	7 00
42	1/4	.25	289	126.00	9.50
42	5/16	.312	360	158.00	12.00
42	3/8	.375	435	190.00	15.00

Table II

located a few feet below the forebay for counteracting water hammer near the power house.

The factor of safety for nearly all material used in pipe lines under high heads ranges from five to six, and it is occasionally eight. (Table II.)

Auxiliaries of Pipe Systems: Forebays, Sand Boxes, and "Grizzles." — Forebays have two functions; namely, to

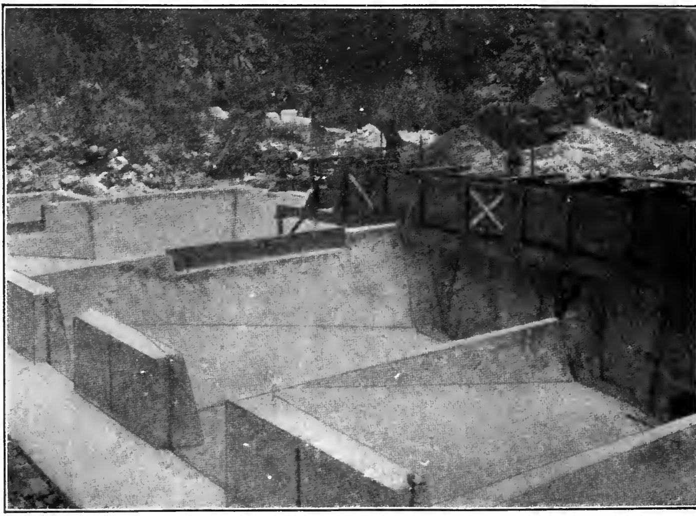


Fig. 23. Type of Sand Box used in Western Practice

allow the water to settle before it is admitted to the pressure pipe, so that sand and silt will be deposited, and to permit submerging the intake of the pressure pipe. Forebays are constructed either of concrete masonry or a natural basin is sometimes taken advantage of by constructing an earthen dam across a canyon or ravine, the bottom of which is sometimes paved with cement.

Sand boxes are placed at the ends of water-conducting systems to prevent sand from entering the nozzles and buckets of water wheels. They usually consist of chambers, or box-like compartments, having a considerable slope from the point where the water enters.

Each of the dividing walls of the chambers except the middle one is designed to be several feet below the surface of the water. The middle wall is slightly higher than the water surface, and thus allows the water to pass through a gate into the connecting pipe line. Fig. 23 shows a sand box of this construction. At the lower end of the compartments is a plug valve provided with a stem that runs up through the water to a board walk above. The valve is lifted by a block and tackle, which opens the orifice in the bottom of a compartment, and by turning water into each compartment the box can be quickly cleared of sand.

Sand boxes are sometimes made of two parallel hoppers with sluice gates in the bottom through which accumulated sand and silt can be expelled. Water is passed through one hopper while the other is being emptied.

"*Grizzles*" are devices for removing leaves, débris, etc., from water-conducting systems.

Conduits and Canals. — The term "*conduit*" as generally applied in hydraulics means a channel of any shape, open or closed, and lined with masonry, concrete, or timber. The word is also applicable to large pipes made of metal or wood.

The term "*canal*" is applied to a conduit excavated in the earth and without masonry or other artificial lining. A common name for a supply canal is "*head-race*."

Conduits and canals are more generally employed for

conveying water to hydraulic plants than any other form of conducting medium. Their usual shape is rectangular, but they may be of either trapezoidal or triangular cross-section.

In regions where the geological formation or character of the soil would occasion considerable loss of water through seepage into the soil, it is considered more advantageous, especially if the conducting channel is long, to line it with concrete or timber.

When a canal pure and simple is used to convey water, the sides and bottom are generally puddled with clay to prevent percolation of the water through the soil. In some cases this is accomplished by sending through a sediment of clay with the water. This is continued until the walls and bottom of the canal are well plastered with the clay.

Concrete pipe or conduit is usually constructed of Portland cement in sections two or three feet long and from one and a half to two and a half inches thick. In the conducting systems of some Pacific coast hydro-electric plants, the material used in the construction of concrete conduits is the natural gravel and sand taken from the wash of the stream, with Portland cement as the binding material.

When the sections of pipe are completed they are cured for a season on the spot. And when the pipe is made in ravines or canyons, as is frequently the case, the sections are hoisted by means of a steel cable to the trench grade on the mountain side above.

Conduits and canals should receive the water from the reservoir in a way that will occasion no loss by leakage, and so that the mouth of the channel can be tightly closed if desired. Means must also be adopted to prevent leaves, trash, gravel, or sand from entering the channel.

BIBLIOGRAPHY

Water Power. Frizell. Third Edition. Wiley & Sons. New York. 1903.

Design and Construction of Dams. Wegmann. Fourth Edition. Wiley & Sons. 1899.

Reservoirs for Irrigation, Water Power, etc. Schuyler. Wiley & Sons. New York. 1901.

A Treatise on Masonry Construction. Baker. Ninth Edition. Wiley & Sons. New York. 1899.

A Method for Determining the Supply from a Given Watershed. Greenleaf. *Engineering News.* Volume 33. Page 238.

A Form of Mass Diagram for Studying the Yield of Watersheds. Horton. *Engineering Record.* 1897. Volume 36. Page 285.

Instructions for Installing Weirs, Measuring Flumes and Water Registers. Johnson. *Engineering News.* August 29, 1901. Page 131.

Commercial Value of Water Power per Horse Power per Annum. Transactions American Society Mechanical Engineers. Abstracted in *Engineering News.* January 22, 1903.

Stave-Pipe. A. L. Adams. Transactions American Society Civil Engineers. 1898. Page 676.

Diagram Giving Discharge of Pipes by Kutter's Formula. Gregory. *Engineering Record.* Volume 42.

Manufacture and Inspection of Cast-Iron Pipe. Wiggen. Journal Association of Engineering Societies. May, 1899. Page 209.

Design of American Dams. *Engineering Record.* February 20, 1902.

Wooden Stave vs. Riveted Pipe. Journal Association of Engineering Societies. Pages 239–262. Philadelphia. 1898.

CHAPTER III

HYDRAULIC MACHINES AND ACCESSORY APPARATUS

Hydraulic Machines. Distinction between a Turbine and a Water Wheel. — When water is admitted to only one part of the circumference of a hydraulic motor the machine is termed a water wheel. When water is admitted around the entire periphery of a hydraulic motor the machine is termed a turbine.

In either case the rotation of the wheel is produced by the weight of water falling from a higher to a lower level, or by dynamic reaction due to a change in velocity and direction of a stream.

According to the manner in which they operate, turbines are divided into two general classes, namely, "impulse" and "reaction" turbines. The essential difference between the two is that in an impulse turbine water enters the machine with a velocity due to the head at the point of entrance in the same manner that it does from the nozzle which actuates the impulse wheel, whereas in a reaction turbine the velocity of the entering water may be greater or less than that due to the head on the entrance orifices; like the reaction wheel it is influenced by the speed of the water. The reason for this is that the hydrostatic pressure of the water is largely transmitted to the rotating wheel — that is, if the spaces between the vanes or buckets are entirely filled.

It is feasible to make any turbine work either as a reaction or as an impulse machine. By actuating it so that the

water passes through the vanes without entirely filling them, the turbine becomes an impulse machine. If, on the other hand, the entering water is obliged to fill all the buckets, the turbine becomes a reaction machine.

It is manifest from the foregoing definitions that the buckets of an impulse turbine are considerably smaller than those of the reaction type.

In order that the entire energy of the water be utilized,

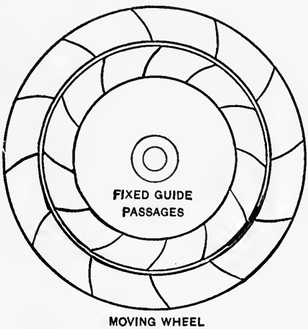


Fig. 24. Outward-Flow Turbine

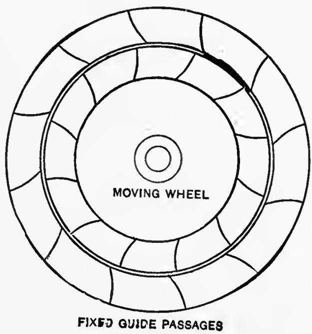


Fig. 25. Inward-Flow Turbine

the vanes or buckets of turbines are curved tangentially, so that the water may react upon the surfaces and deliver as much energy as possible.

Kinds of Turbines.— Turbines are classified according to the way in which water is passed through them into "outward-flow," "inward-flow," and "downward-flow" turbines.

In an outward-flow turbine water enters around the complete inner periphery of the runner and is discharged around the entire outer periphery. In an inward-flow turbine the motion of the water is exactly opposite.

In the downward-flow turbine water is admitted around

all the upper annular openings, and is shot downward between the rotating vanes, passing out through the lower annulus.

The normal speed of an impulse turbine is somewhat lower than that of a corresponding reaction turbine operating under the same head, but the entrance velocity of the water is considerably greater in the impulse type, which means that considerably more energy is liable to be wasted by shock and foam.

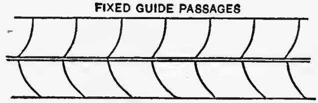


Fig. 26. Downward-Flow Turbine

Fig. 24 shows an outward-flow turbine, Fig. 25 an inward-flow turbine, and Fig. 26 a downward-flow turbine.

Conditions to which Impulse and Reaction Turbines are Adapted. — The type of hydraulic machine which should be adopted in any particular case depends upon the height of head which is to be utilized. In general, for low heads, — *i.e.*, up to 45 feet, — the impulse or "American" type of turbine, mounted on a horizontal or vertical shaft, with open flume (and usually with draft tube), should be employed.

For moderate heads, ranging from 45 to 400 feet, the reaction turbine (with radial inward flow), mounted on a horizontal shaft and fitted with a cast-iron case and draft tube, should be employed.

For high heads, *i.e.*, those ranging from 400 to 2,000 feet or over, the Pelton type of wheel or the radial outward-flow machine, mounted on a vertical shaft and contained in a cast or wrought iron case, with draft tube, should be used.

A reaction turbine, as stated previously, is rotated by the dynamic pressure of moving water, which may also be more or less under static pressure. Hence, the particular sphere of work to which the reaction machine is suited is under conditions where a large quantity of water under a moderate head must be handled.

As regards the conditions for which the impulse wheel is well adapted, it may be said in general that for heads ranging from 100 feet upwards this type of wheel is the only practical form, capacity and size being equal.

When a hydraulic machine is driving an electric generator it becomes imperative to maintain a practically constant speed irrespective of changes in the load. In this respect a reaction turbine cannot compare with an impulse water wheel, since a change in its speed involves a considerable loss in efficiency. In an impulse wheel water can be admitted through a part of the guides, which with a reaction turbine is manifestly infeasible.

The efficiency of an impulse wheel is not appreciably diminished by a partial closing of the admission gates, but with a reaction turbine the abrupt increase of cross-section beyond the partly closed gates causes a considerable diminution of efficiency. The normal speed of an impulse wheel is constant for all positions of the gate. With a reaction turbine the speed is considerably less at partial than at maximum gate.

Efficiencies of Hydraulic Machines. — The efficiency of hydraulic motors depends upon the following conditions: (1) The water should enter the machine without producing appreciable shock. (2) It should be discharged from the machine at a low velocity. (In general the lower the velocity in the tail race, the greater the amount of useful

work which the motor has abstracted from it.) Or the water should enter the buckets without shock and leave without velocity. (3) The buckets or vanes of the turbine should be so curved as to receive the full impact of the nozzle jet. (4) The water supply should be free from sediment, sand, leaves, or other organic matter. (5) The rotating member of the turbine should revolve in its bearings with the minimum of friction.

The efficiencies of American-made hydraulic machines range from 65 to 85 per cent, depending upon the design,

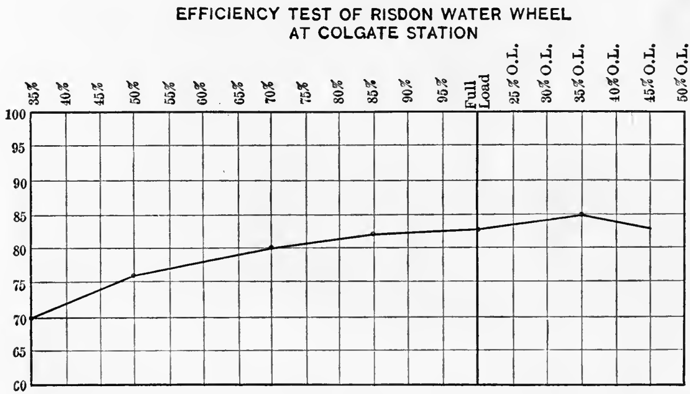


Fig. 27

output, and conditions of operation. The majority of machines of moderate output will not exceed 70 per cent in efficiency. Fig. 27 shows the efficiency curve of a 3,000 horse-power Risdon impact wheel.

The importance and desirability of employing the most efficient turbine commensurate with the permissible outlay cannot be over-estimated. In cases where the water supply is uncertain or limited it becomes almost imperative to

adopt a machine which will transform the kinetic energy of the water into the maximum mechanical power. Especially is this true in cases where the water is bought or power sold.

In the *Engineering News* of December 4, 1902, Mr. John W. Thurso admirably shows the great importance

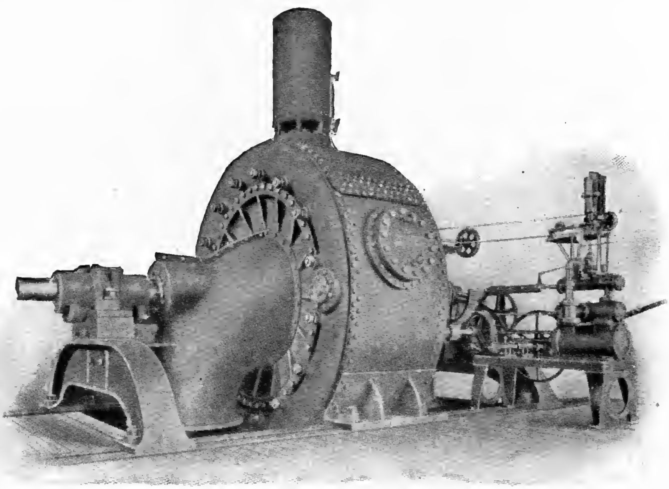


Fig. 28. Samson Niagara Type Turbine

of using an efficient turbine. He says, "Supposing that power is sold at $15 per year for an effective mechanical horse-power at the turbine shaft, and that the water supply is limited. The amount of water required to develop one effective horse-power with 70 per cent efficiency will give 1.143 horse-power, worth $17.14 per year, with 80 per cent efficiency.

"The difference of $2.14 in favor of the turbine with higher efficiency is equal to an interest of 15 per cent as

above on $14.27 ; or a 1,000 horse-power turbine giving 80 per cent efficiency could cost $14,267 more than a turbine giving 70 per cent efficiency *without being more expensive*."

Types of American Turbines. — Fig. 28 shows one form of the Samson turbine made by the James Leffel Company. It is of the double-discharge horizontal form, and is

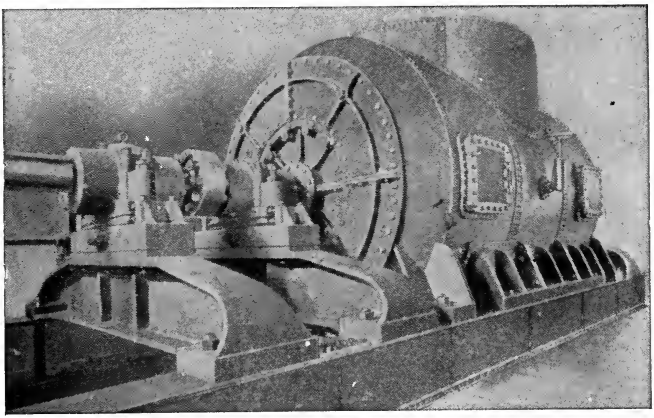


Fig. 29. High-Head Heavy Duty Turbine

called the Niagara design. This type is usually fitted with one runner and two similar sets of buckets. The entering water is equally divided between the two sets of guides and is discharged in opposite horizontal directions. This form of turbine is fitted with an outer casing, thus affording an easy circulation of water around the guides on the runner. Water is admitted to the casing either from below or at any desired angle from a horizontal or vertical line on top.

The shafts revolve in ring-oiled bearings supported by

heavy iron bridge-trees. The illustration shows a 2,400 horse-power machine for direct connection.

Fig. 29 shows a high head, heavy duty, center discharge, horizontal shaft Samson turbine. It consists of two 56-inch turbines mounted on a bronze shaft and fitted with bronze runners and balanced steel gates.

The type of runner used on Samson turbines is shown in Fig. 30, which is an illustration of the vertical shaft type. The runner is made up of two distinct forms of wheels which have different diameters. Each set of buckets comprising a wheel receives its separate quantity of water from the same set of guides, and discharges to the outlet; the water does not act twice upon the combined wheel.

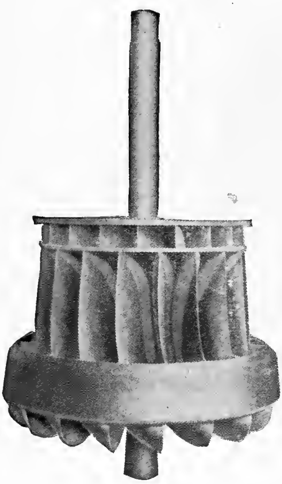


Fig. 30. Runner of Samson Turbine

Fig. 31*a* shows a 55-inch Victor high pressure turbine made by the Platt Iron Works. This turbine develops 8,000 horsepower under a 630-foot head and is controlled by a Lombard governor. The illustration shows the water supply connection below the floor level, also the by-pass valve.

Fig. 31*b* shows this type of turbine coupled to an alternator.

The Victor machine is a mixed-flow type, water entering radially inward at the circumference and discharging downwards and outwards. The whole depth of the wheel

proper is occupied by the buckets, which are deep axially, thus giving large capacity for its size.

Water supply to turbines is regulated by two types of gate, one of which is termed the *register gate* and the other the *cylinder gate.* The former admits water to the turbine by turning about the axis of the wheel, thus

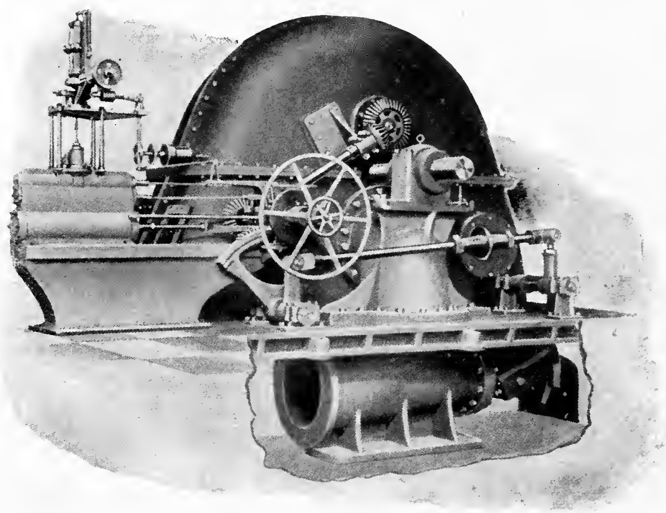


Fig. 31a. Victor High-Pressure Turbine

opening the passage wider and wider as it is turned more and more, and at the same time giving direction to the water. The cylinder gate is the preferable form when the water supply is variable or when the work is variable: the cylinder gate is also better adapted to low and medium heads.

Fig. 32 shows a pair of 42-inch McCormick turbines made by the S. Morgan Smith Company. The machines are

designed for direct connection to an electric generator, and develop 4,000 horse-power at 300 revolutions per minute under a 72-foot head. The illustration also shows a single 400 horse-power turbine for driving the generator exciter.

Water Wheels — Principles of Operation: Features upon which Speed and Power Depend. — A hydraulic machine, as has been already stated, is known as a "water wheel"

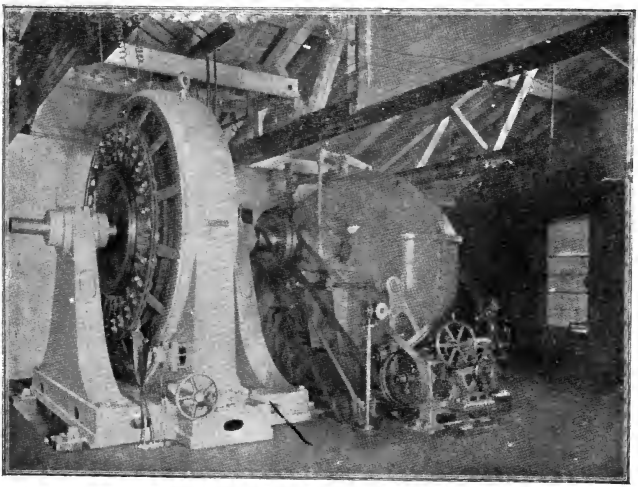


Fig. 31b. A 1,000 Horse-Power Turbine Coupled to Alternator

when water is admitted to one part of its circumference. Since this type is driven by the impact of a jet or jets of water against buckets mounted on the periphery of a wheel it is termed an "impulse wheel."

In general the impulse wheel is the most practical form of machine that can be employed when the head is above 100 feet, and for very high heads it is the only type of machine that can be employed. The buckets of water

wheels are curved tangentially or ellipsoidally, the object in either case being to oblige the water to react upon the bucket surfaces so as to give up the maximum amount of its energy.

Water is conducted to an impulse wheel through the various types of artificial channels described in the preceding chapter, and is delivered to the buckets through a nozzle, the end of which is fitted with a cylindrical tip, the diameter

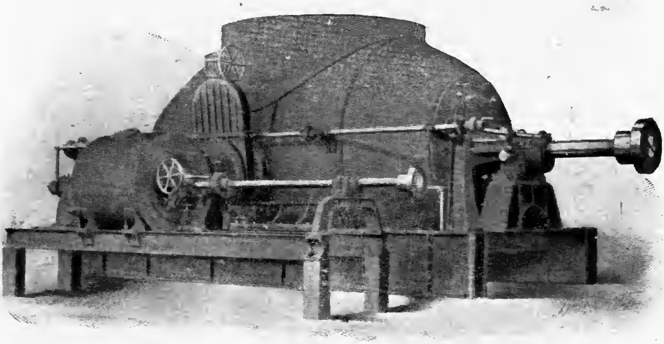


Fig. 32. A Pair of 4,000 Horse-Power McCormick Turbines

of which is proportional to the head of water and the amount of power to be developed. Since tips of different diameters can be screwed into the nozzle it is thus possible to vary the power of the wheel from the maximum (limited by the size of the buckets) down to a small percentage of the rated capacity. The use of varying sizes of nozzles thus permits of maintaining a nearly uniform efficiency at all stages of load.

When it is desired to double or treble the output of a water wheel without increasing its diameter, two or three nozzles are employed, the consumption of water being correspondingly increased, of course.

The power of a water wheel, strictly speaking, does not depend upon its dimensions, but upon the head and quantity of water supplied to it.

The speed of a water wheel depends upon its diameter, and when operating under a given head the number of revolutions which it maintains should be constant, regardless of the amount of power it is developing.

Water wheels are constructed to operate in either a vertical or horizontal plane, the horizontal type, however, being more commonly employed. In the horizontal type the wheel is supported on a shaft running in journal boxes, the entire running mechanism being inclosed in an iron casing divided in a horizontal plane. When the wheel is mounted in a vertical plane the shaft is provided with a step and thrust bearing.

The buckets of water wheels are constructed of phosphor bronze, cast steel, or cast iron, depending upon the conditions under which the wheel must operate, — *i.e.*, the head of water and the character of the water supply, its freedom or non-freedom from abrasive material in suspension.

Power of a Water-Fall Utilized by a Hydraulic Machine. — Representing the pounds of water delivered per second to a hydraulic machine by W, and considering h as its effective head in feet as it enters the machine (the head h may be due to either pressure or velocity or to pressure and velocity combined), then the theoretical power in foot-pounds per second of the water is

$$K = Wh,$$

and the theoretical horse-power of the water as it enters the machine is

$$HP = \frac{Wh}{550}.$$

On account of losses in impact, friction, etc., the actual horse-power of a hydraulic machine is considerably less than the theoretical horse-power of the water.

Using k to indicate the work delivered by a hydraulic machine, and e its efficiency, then,

$$e = \frac{k}{K} = \frac{k}{Wh}, \quad \text{and} \quad e = \frac{h.p.}{H.P.},$$

a fair average for wheels of moderate output being 75 per cent. The average efficiency of wheels of even comparatively large output is rarely over 78 per cent, and their all-day efficiency will barely exceed 60 per cent.

Effective Head on an Impulse Wheel. — When water is conducted through a nozzle or a pipe line to a water wheel, the head h is not the maximum head, since a considerable portion of this latter head is lost in friction in the pipe system. Hence the head on the turbine or water wheel is really the velocity head, $\frac{V^2}{2g}$, of the jet.

Having determined the value of V from the discharge q, and the area of the cross-section of the stream, the effective head on an impulse wheel is

$$h = \frac{V}{2g} = \frac{q^2}{2ga^2},$$

in which q is the discharge, and a the area of its cross-section.

Speed Regulation of Water Wheels and Turbines. — The three general methods for regulating the speed of water wheels are:

(1) By means of a deflecting nozzle; (2) by a plug nozzle; and (3) by the use of a cut-off hood. In each

method the controlling device is always actuated by some form of automatic governor, the function of which is to adjust the position of the device to suit the demands of the load.

The deflecting nozzle is usually of cast iron and fitted with a ball and socket joint, which permits of its being raised or lowered, thereby throwing the nozzle on or off the buckets. Thus the power output of the wheel is increased or decreased to meet a change of load, and the

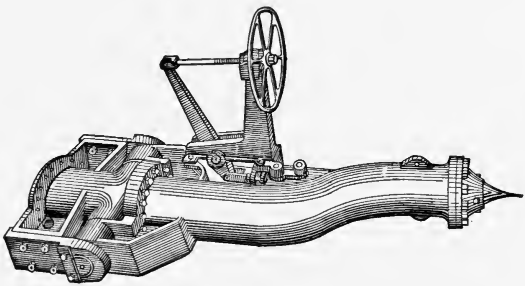


Fig. 33. Deflecting Nozzle

speed is kept uniform. A modification of this speed-regulating device consists of a plate which deflects the stream, the nozzle being kept stationary. Fig. 33 shows a deflecting nozzle.

A plug nozzle is a nozzle body fitted with a concentric tapered plug. By changing the position of this plug a change is produced in the discharge area of the nozzle, thereby varying the amount of water consumed by the wheel, the power output being governed accordingly.

A cut-off hood consists of a spherical plate fitted tightly over the end of the nozzle. Variation in the position of the

hood produces a change in the discharge area of the nozzle, thus varying the power of the wheel.

The speed regulation of turbines is accomplished almost universally by means of gate valves controlled by some form of governor, the function of the governor being to open or close the water supply orifice to an extent corresponding to the increased or decreased demand for power.

Perfect speed regulation of hydraulic machines is impossible, owing to two limitations: (1) Such limitations as are imposed by the governor itself, and (2) those imposed by the inertia of the masses upon which the governor acts to control the speed.

Governors — Requisites of a Good Governor. — The most important desiderata which a good governor should possess are simplicity, ability to regulate closely the speed of the hydraulic machine, freedom from racing and hence avoidance of unnecessary movements of the gate, freedom from all shocks and jerky movements, adaptability to all kinds of plants, reliability of operation, and low cost of maintenance.

The chief limitations possessed by all forms of governors are due to the fact that there must be a speed variation to some degree before the governor can begin to operate, and a definite time is required to adjust the gate to its new position. Moreover, the initial change must become appreciable before the governor operates the gate at its maximum speed, but the appliances used to prevent the overspeeding of the gate invariably exercise a dampening effect upon the speed of the gate movement while it is motive.

The secondary limitations, or those due to the inertia of the masses to be moved, are far more complex. These are

due to the sluggishness of movements of the various components of the gate, such as the shafts and the rigging, and to the inertia of the water to be controlled.

Kinds of Governors — Principles of Operation. — Governors for regulating hydraulic machines are, (1) those operated by the pressure of a fluid, which may be oil or water; (2) mechanically operated; (3) electro-mechanical, or (4) induction motor governors.

Governors of the first kind are generally termed "hydraulic" governors. The fluid used for operation depends on the conditions which must be met, as well as considerations of cost and maintenance. In general oil-pressure governors are used for low heads, while the water-pressure form is employed for heads above 100 feet. The essential elements of a hydraulic governor are, a cylinder fitted with a shaft or piston which actuates the water gate; a hydraulic valve or valves working in a chamber, and controlling the pressure applied to the hydraulic cylinder; a centrifugal governor for controlling the movements of the main valve; an auxiliary controlling device which determines the amount of the gate opening for any definite variation of load; some form of anti-racing mechanism; some form of controller for determining the rate of speed at which the governor shall operate, and a power pump (if the governor is of the oil-pressure form).

Mechanically operated governors usually consist of a train of gear wheels, driven by the governed unit and fitted with a centrifugal speed-regulating device which permits the governor to trip some mechanical device for moving the water gates.

Electro-mechanical governors operate by means of electro-magnets which throw reciprocating pawls into oper-

ation, these pawls being so arranged that they actuate the regulating mechanism of the wheel.

Governing by electric (induction) motors has been successfully applied in one or two Western hydro-electric plants to small impulse wheels driving exciter dynamos. The speed regulation of the turbo-generator unit in this case depends upon the principle of the induction motor in running below synchronism normally, and of giving no mechanical output of power when driven at synchronous speed. When driven above synchronous speed by extraneous means current is delivered instead of consumed. In the case under discussion the motor is run above synchronism, and thus absorbs the surplus energy of the water wheel over that demanded by the exciter dynamo. But when the load on the exciter becomes of such a value that the water wheel is unable to take care of it, the motor ceases to generate current and performs its function of motor, thus helping the water wheel. When the water supply of the wheel is accidentally or purposely cut off, the motor can be used to drive the exciter dynamo. Thus it can be made to perform the function both of a water wheel governor and a prime mover. In the cases where the electric motor has been employed as a governor it is mounted on the same shaft with the water wheel.

Switchboard Control of Governors. — The control of governors from the switchboard greatly reduces the time and labor necessary to effect a variation in the speed of a hydraulic machine, and also simplifies the method of speed regulation considerably. This plan of governor operation readily enables the switchboard attendant to start, stop, or alter the speed of a single machine or of all the machines under his care, from one central point.

In this method of operation a small alternating current motor performs the work of shortening or lengthening the valve stem, instead of the attendant's fingers. Hence this dispenses with the practice of having one man to watch the synchronizing lamps and another to attend the governor and vary its speed in accordance with the signals given from the switchboard, so that the switchboard attendant can perform any or all of the operations of starting or stopping or synchronizing machines thrown in parallel, without outside assistance.

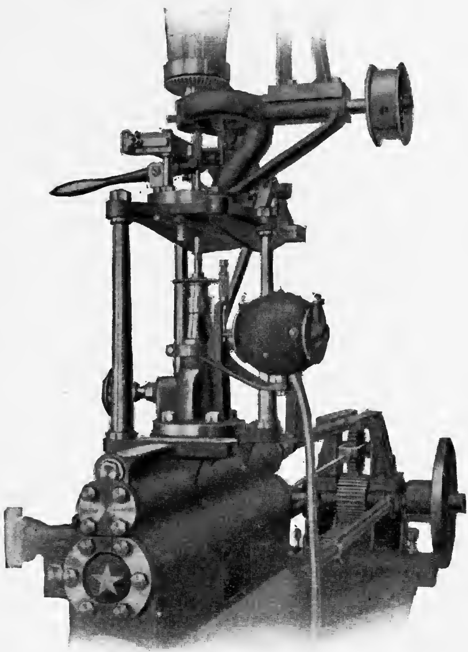


Fig. 34. Electric Speed Controller for Governors

Fig. 34 shows the electric speed controller of the Lombard Governor Company. In this type of controller a small fan motor of about one sixteenth horse-power is attached to a bracket, which is clamped to the governor regulating valve. The armature shaft of the motor carries a small worm, which drives a worm gear on a vertical pinion shaft.

The pinion imparts a rotary motion to another gear which is threaded through its hub, and so acts as a right and left coupling to force together or push apart the two portions of a valve stem upon which it rotates. The pinion is made of sufficient length so as not to interfere with the up and down travel of the gear. Current for operation is obtained either from the exciter circuit or from batteries.

The controlling apparatus consists of a small reversible motor connected by double reduction worm gearing to the bracket supporting the controlling lever of the governor. The motor imparts an endwise thrust to this bracket, which in turn shifts the position of the controlling lever, and thus causes a variation of the speed at which the governor has been maintaining the turbine.

The switch which controls the motor, and which may be located at any point desired, such as a switchboard, has two buttons for raising and lowering the speed, and a small thumb switch for entirely cutting out the apparatus when it is not in use. The thumb switch is fitted with three contacts, one of which is employed for quickly stopping the unit without requiring the attendant to depress the push button while this is being done. Automatic cut-outs are used on the motor to prevent its overrunning when the lever has reached its limit of movement.

Types of American Governors.— A type of fluid pressure governor quite extensively used in hydro-electric plants is the Lombard, made by the Lombard Governor Company, of Boston. Fig. 35 shows the type "D" Lombard oil pressure governor. The cylindrical tank which is contained under the bed of the governor is divided into two compartments, the dividing partition being located at the point indicated by the row of rivets.

The larger part of the cylinder (to the left) is filled about half full of oil, while the upper part of the larger compartment of the pressure tank is filled with air under a pressure of approximately 200 pounds per square inch.

The smaller compartment of the cylinder contains a

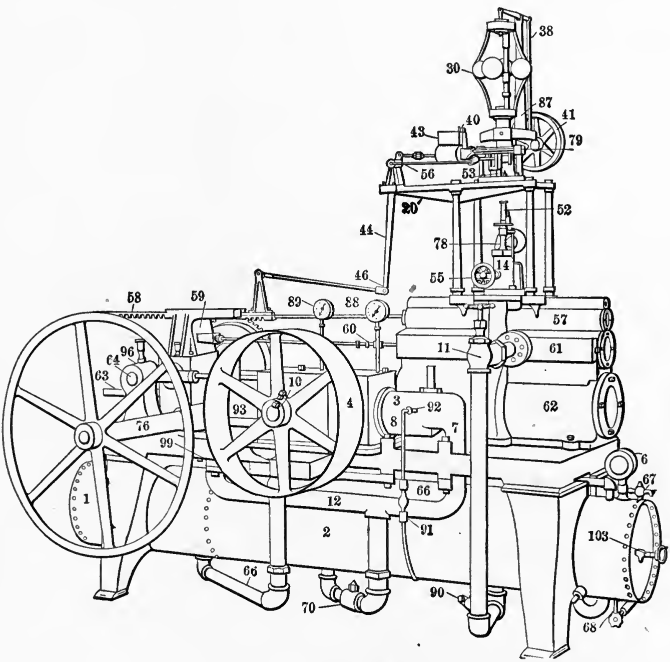


Fig. 35. Oil Pressure Governor for Moderate Sized Turbines

vacuum. Both pressure and vacuum are constantly maintained by means of a pump placed on the farther side of the governor bed and driven by the larger pulley, this being belted so as to revolve continuously when the governor is in operation.

The movement of the water wheel gates takes place

when oil from the pressure tank is let in on one side of the piston. Immediately this occurs, oil on the other side of the piston is discharged into the vacuum tank, from whence

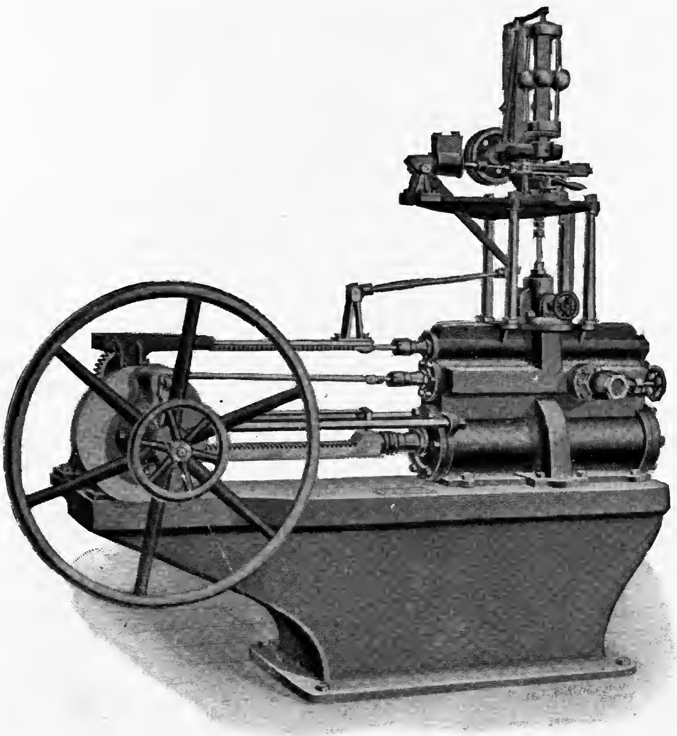


Fig. 36. Governor for Impulse Water Wheels

it is at once pumped into the pressure tank. The piston rod is terminated in a rack which is geared positively to the gate shaft. A full stroke of the piston rod completely opens or closes the water wheel gates ; intermediate or

partial motions of the piston causes correspondingly smaller movements of the gates.

The oil pressure type of governor is coming into greater use in American hydraulic plants, as it has been found from practical experience that it is more certain and positive in its operation than the water pressure type, owing to the fact that it is extremely difficult to prevent grit, sediment, or other organic matter from entering the governor supply pipe, thereby clogging up and hindering the quick operation of its mechanism.

The frequent cleanings thus required in some cases render the use of the oil pump far more satisfactory, notwithstanding it is troublesome to maintain.

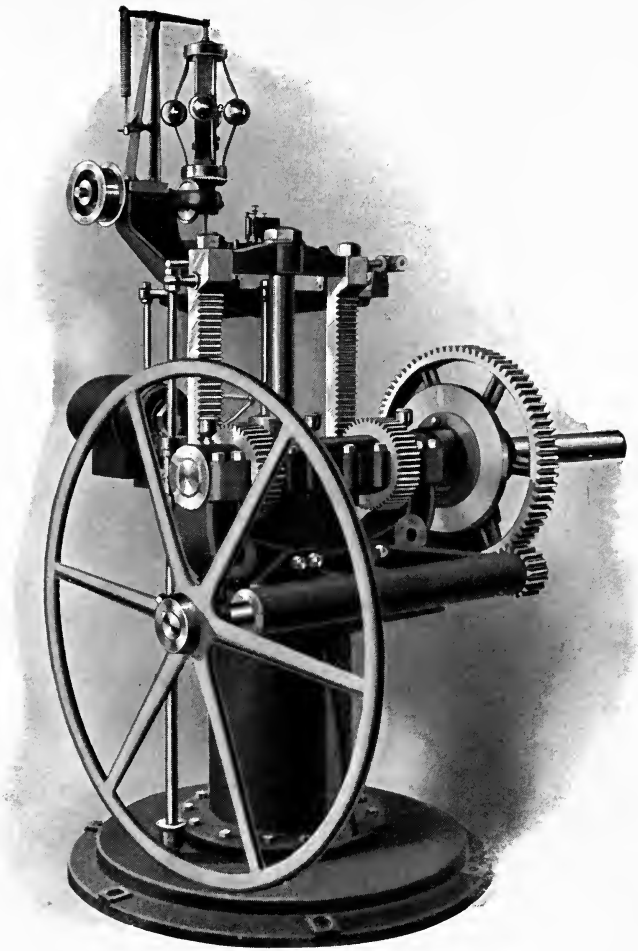
The type "L" Lombard water pressure governor shown in Fig. 36 is primarily designed to regulate large tangential water wheels, but is also applied to the regulation of turbines of moderate size under high head.

The general construction of the governor can be clearly seen in the illustration. The terminal shaft in this type makes 1.52 revolutions to open the water wheel gates and rotates clockwise to open them.

As in the oil pressure type, the small hand wheel actuates a pin clutch, which permits of the operation of the water wheel gates by means of the hand wheel if desired.

The piston is terminated in a rack which rotates a gear sector, the central shaft of which is geared or coupled directly to the rock shaft which controls the deflecting nozzle.

As the piston travels in or out the nozzle deflects the water on to or off from the water wheel, or opens or closes the gates of the turbine, as may be the case to which the governor is applied.



F.g. 37. **Type N, Lombard Water Wheel Governor**

Some American water wheel governors embody the relay principle of operation, which permits the governed unit to run at a slower speed when loaded than when running empty.

The object of this is to gradually and systematically use the stored energy in the rotating parts of the hydraulic motor.

The Lombard Type "N" oil pressure governor shown in Fig. 37 is equipped with the relaying valve mechanism and is especially adapted to the requirements of large water wheel units. One large casting forms the main cylinder and the bearings for the terminal shaft. The base forms the lower cylinder head and the upper cylinder head is integral with the cylinder; the object of this construction being to obtain maximum strength with least weight of metal and to obviate the possibility of joints loosening under the great stresses involved. The linear motion of the piston is transformed by racks and pinions to rotary motion at the terminal shaft. In order to reduce the vertical height of the governor and also to transmit the force of the piston to the rotating shaft efficiently, double racks and pinions are used, the racks being connected to an equalizing yoke, and the racks are placed alongside of the cylinder instead of beyond it.

The steel terminal shaft is $2\frac{15}{16}$ inches in diameter and is supported by bearings on both sides of the piston. The main piston rod gland cap is cup-shaped so as to prevent leakage over the machine. The usual form of hand wheel is employed which is thrown out of gear when the governor is in regular operation.

The main valve of the governor consists of a large double hollow piston contained in the horizontal cylindrical case back of the rim of the hand wheel at the left of the figure. The valve is perfectly balanced so as to require a very slight force to move it, but in order to insure absolute reliability of movement hydraulic plungers are also provided. These plungers are simultaneously actuated by a small primary

valve secured to the stem of the centrifugal balls, and a small valveless displacement pump in the slender vertical cylinder at the left of the illustration (Fig. 37). The piston

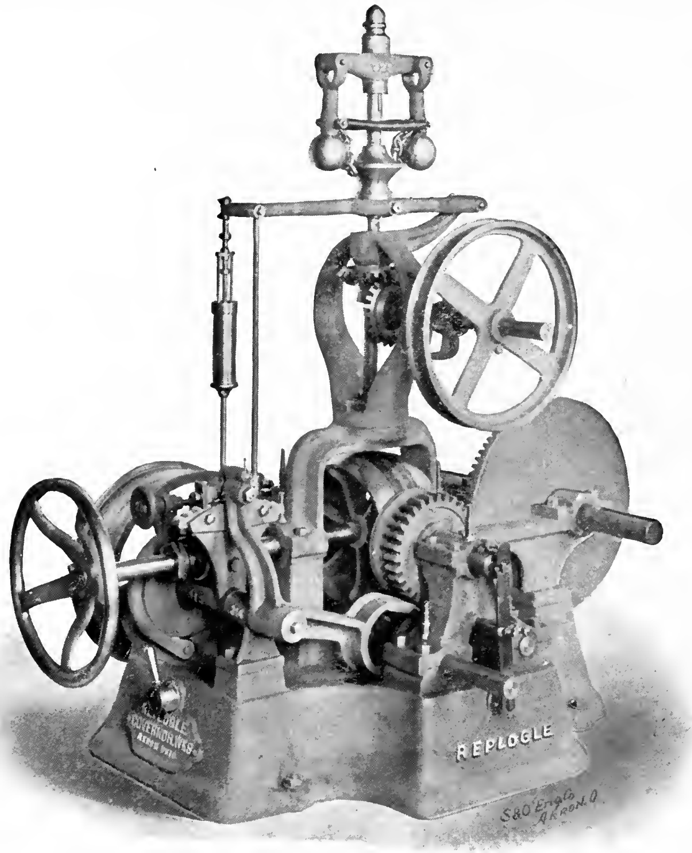


Fig. 38. Duplex or Differential Relay Governor

of this pump is attached to and moves with the main piston of the governor. These parts are so disposed with respect

to each other that the slightest displacement of the primary valve by the centrifugal balls causes an instantaneous and positive movement of the large main valve. The main valve is instantly restored to its closed position by the action of the displacement pump as soon as the primary valve is again closed. The movement of the primary valve results in an instantaneous magnification and insures accurate speed regulation.

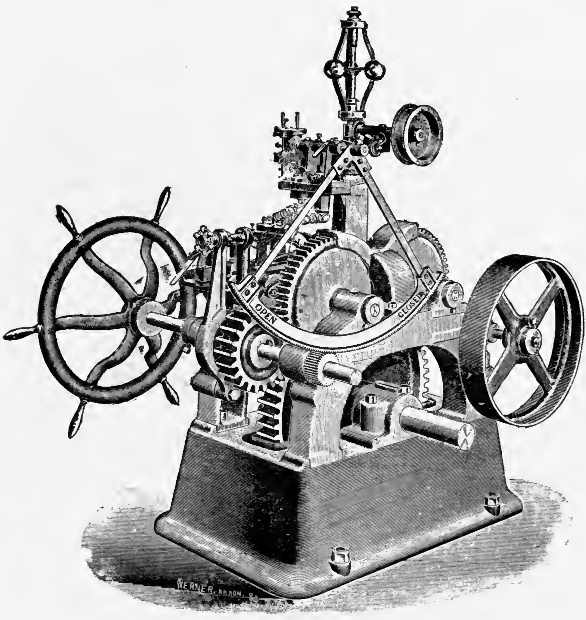


Fig. 39. A Relay Returning Governor

The working fluid for this governor is a special oil kept under pressure in a vertical draw steel tank. Oil is forced into this tank by a powerful pump which is an accessory of the governor. The normal pressure under which the governor works is 200 pounds per square inch, at which pressure it exerts the powerful force of 31,000 foot-pounds per stroke.

A duplex relay governor made by the Replogle Governor Works is shown in Fig. 38. The operation of this governor is on the principle that a movement of the gate automatically cuts the governor out of action, to obviate racing or hunting when the load is varied. Or stated otherwise, there is a rapid movement of the wheel gates to correspond with the variation in load at the time of its variation; the gate movement being arrested in time to permit gravitation to correct momentum and inertia effects. It is claimed that this governor is geared to swing a gate completely in from 15 to 25 seconds.

Fig. 40. Sturgess Oil Pressure Governor

A relay returning governor, made by the Replogle Company, is shown in Fig. 39. The returning principle when added to the relay governor is claimed to restore the speed always to normal, leaving it identical with the speed at no load.

A type of governor of the hydraulic class, made by the Sturgess Governor Engineering Company, is shown in Fig. 40. This form is designated type "A," and is designed for operation by oil pressure. The main elements of the governor consists of (1) a shaft and

piston working in an hydraulic cylinder and actuating the gate; (2) a main valve, hydraulically operated, for admitting pressure to the hydraulic cylinder; (3) a centrifugal governor for controlling the motions of the main valve; (4) a secondary controller for gauging the amount of gate movement for any given variation in load. The governor here shown has a power factor of 35,000 pounds, and is designed for units above 2,000 horse-power.

Lyndon "Rapid" Water Wheel Governor. — A water wheel governor which embodies some novel features has recently been invented by Mr. Lamar Lyndon. This machine is claimed to give very close regulation in ordinary power plants where economy of water is important; and in such plants where the flow of water exceeds the amount of water used in the water wheels, regulation approaching that of high-speed engines is said to be possible.

The governor is of the electrical type and consists essentially of a solenoid controller with an electrical contacting device which energizes magnetic clutches; a small dynamo; a compensating valve; a manually operated speed changer; and an arrangement of resistances which prevent over-running of the gates.

The compensating device is a simple butterfly valve working in a by-pass pipe which is tapped into the flume or penstock of the hydraulic machine. Its location and operation are indicated in Fig. 41. As is obvious, all water by-passed through the valve and auxiliary pipe goes around the turbine and does no work.

In such plants where the quantity of water exceeds that admitted to the turbines, the compensating valve is adjusted

to half-way position and a continual flow through it results. Increase of load on the turbine, which causes the turbine

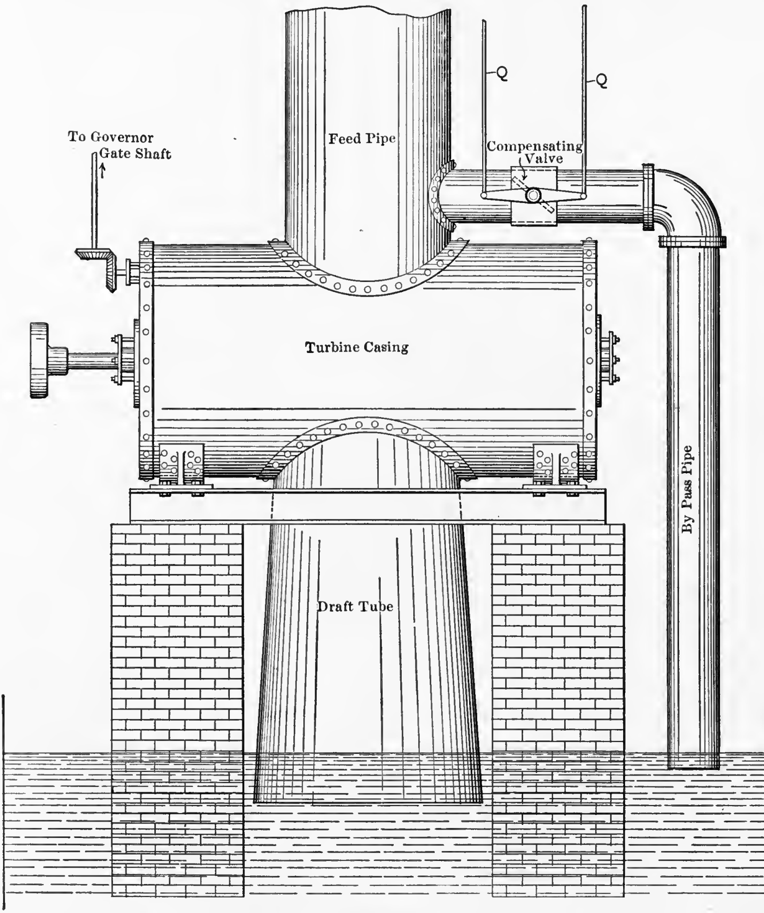


Fig. 41. Arrangement of Compensating Valve, Lyndon Governor

gate to suddenly open, causes the compensating valve to close at the same rate of speed as the turbine gate

opens. This admits an increased amount of water into the turbine, without necessitating any change in the velocity of water in the feed pipe; which permits a very quick speed regulation. After the turbine gate has found its new position and regulation is completed, the compensating valve returns slowly to its normal half-

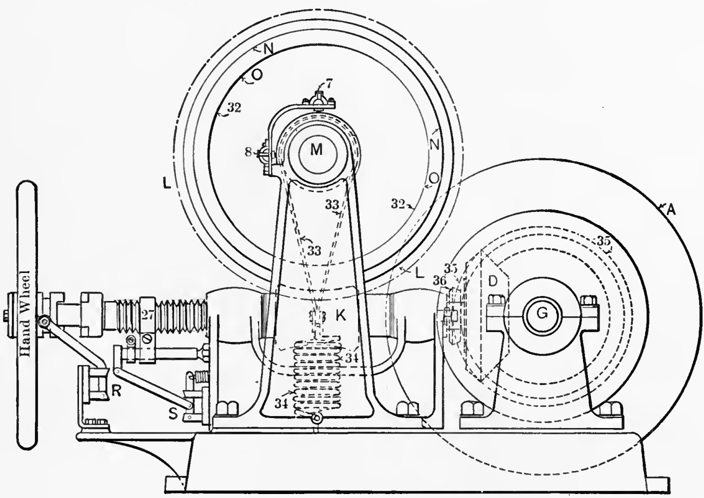


Fig. 42. Side Elevation of Lyndon Governor

way position while the velocity of the column of water in the feed pipe also changes slowly to furnish the increased supply.

Should the load on the turbine decrease, and the gate thereby suddenly close, the compensating valve will open, the movement occurring inversely to the movement of the main gate. The outlet for the water from the feed pipe being increased, a less amount will pass to the water wheel,

and therefore the suddenly decreased gate opening does not mean that the velocity of water in the feed pipe is suddenly arrested and great pressure set up. The velocity and pressure remain practically unchanged.

In such plants where all the available water must be converted into work, this governor will not afford so accurate regulation but will give a very uniform speed. When used in such plants the compensating valve is normally fully closed.

A side elevation of the Lyndon Governor is shown in Fig. 42. Fig. 43 is a diagrammatic representation of the parts and connections. It consists of a shaft *G* driven from the turbine to be controlled. Keyed on it are two iron plates *E* and *F*, which rotate with the shaft and magnetically are clutched with plates 30 and 31 respectively. The plates 30 and 31 are secured to miter gears *B* and *C* respectively, which are also loose on the shaft. When either electric clutch is energized, the miter gear connected to the clutch plate will turn with the shaft. Meshing with the miter gears *B* and *C* is a third gear *D*, which is keyed on to shaft *H*, turning at right angles to shaft *G*. If clutch plate 30 is energized, shaft *H* will be caused to rotate in one direction by the gear *B*, while if clutch plate 31 be energized, the shaft *H* will be made to rotate in an opposite direction by gear *C*.

On shaft *H* is mounted a worm *K*, which meshes with a worm wheel *L*, the latter being mounted on a third shaft *M*, which is parallel to shaft *G*. This shaft *M* is the gate shaft, and any movement of it will cause opening or closing of the water wheel gate.

It is obvious that the gate will be opened or closed according to whether *E* or *F* is energized. On shaft *M* is

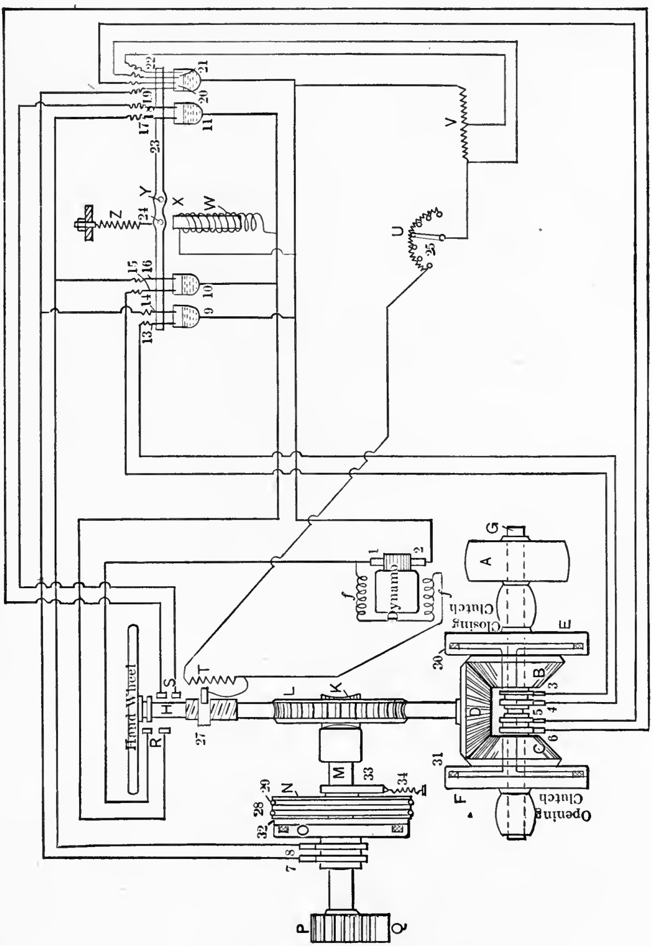


Fig. 43. Parts and Connections of Lyndon Governor

a third magnetic clutch consisting of the plates *N* and 32, *N* being a sheave wheel, having two grooves in it in which lie the wire ropes 28, 29. These ropes are attached to the compensating valve. When the clutch *N* is energized, 32 will be caused to rotate in one direction or the other according to the direction of motion of the gate shafts, while the ropes will move the compensating valve in one direction or the other at the same time that the gates are moved.

Passing over the hub of *N* is a heavy leather strap 33 which has its lower ends attached to spring 34. Obviously this spring is extended whenever *N* rotates in either direction (rotation is limited to about 80 degrees).

The small dynamo which supplies the energizing current is driven from the shaft *G* by means of gears, and therefore varies its speed with that of the water wheel. It is shunt wound with laminated fields and the magnetic density is low; therefore the voltage will vary as the square of the speed.

The controller consists of a plain solenoid *W* which is connected with the dynamo having inside it an iron core *X*. The passage of current through the solenoid tends to draw down the core, such pull varying as the square of the voltage. Since the voltage varies as the square of the speed, the pull on the solenoid will vary with the fourth power of the speed.

The governor is electrically operated in the following manner. Referring to Fig. 43, when the speed is normal the lever 23 is in a horizontal position, none of the contacts touching the mercury in the cups except point 22, which is longer than the others. When the core is pulled down by increase of voltage, contacts 13 and 15 will connect the dynamo circuit with clutch 30 which will cause the gate

shaft to move in a direction to close the gate. At the same time clutch 32 will be connected to the dynamo circuit by contacts 14 and 16 and the sheave wheel will also turn with the gate shaft.

If a drop in voltage occurs, causing the core to rise, the gate opening clutch will be energized by contacts 18 and 20, while the sheave wheel will turn in a direction opposite to that in which it rotates when the gate closes, its clutch now being energized by contacts 17 and 19. Thus the compensating valve is always moved in its proper direction whenever the main gate is moved.

When governing is completed and the speed becomes normal, the lever 23 takes a horizontal position, thereby opening the clutch circuits, and the compensator sheave *N* is drawn by the spring 34 back to its normal position. The water flowing through and surrounding the valve gives a dash pot action and makes this return movement take place slowly. Contacts 21 and 22 change the amount of resistance in the dynamo field with movement of lever 23 and thereby tend to restore the dynamo voltage to normal before the dynamo speed has come to its proper value; and this arrangement prevents "overrunning" or "hitching" of the gates. Since the gate movement in this type of governor takes place quickly, these machines are made very heavy and powerful.

Testing of Turbines and Water Wheels. — The data on the output, efficiency, and behavior of their wheels are usually obtained by makers of hydraulic machines from tests conducted at the Holyoke testing flumes. As it is generally too expensive for the purchaser of a wheel to fit up the necessary apparatus for checking up the manufacturer's data, it is often specified in the contract that the

wheel be sent to a place where all the special facilities for the test are available. The purposes of the tests are usually the determination of effective energy and power of the wheel; the determination of efficiency; the determination of the speed which gives the maximum power and efficiency.

The wheel is mounted in the testing flume, and run at different speeds, in order to ascertain the speed which gives the maximum efficiency and also the effective power output at each speed. Since the efficiency of hydraulic machines varies appreciably with the position of the gate, tests are conducted with the water gate completely opened, as well as at various intermediate positions.

Such tests afford the necessary information as to effective power and efficiency under various conditions of operation, and also the consumption of water under different heads. The measurement of effective power is usually made by means of a Prony brake, but is sometimes determined by coupling the wheel to an electric generator and absorbing the power in a water rheostat.

Although the tests at the Holyoke flumes are accurately made, they may be quite untrustworthy to the turbine user, since the data obtained at the standard flume may be considerably altered under different conditions of wheel settings, flumes, and chamber proportions. Thus, the actual working conditions to which the user must adapt his wheel often cause the machine to fall short considerably of confirming the manufacturer's data.

Faults of Turbines and Water Wheels. — The principal faults of hydraulic machines are those in design and construction, and such faults as arise from bad settings and improper wheel cases. The result of such errors is a

machine of low efficiency and short life, as well as abnormal cost of maintenance. Until recently the turbine was not regarded as a machine of the highest importance; hence its design has been badly neglected and nicety of constructive details disregarded. Moreover, the material and workmanship were, and are still in many cases, of a very low

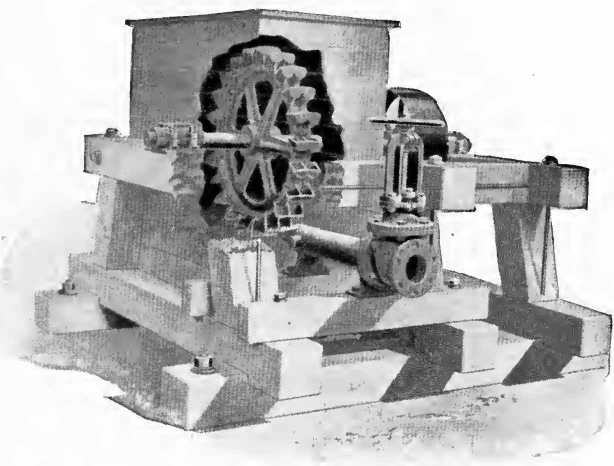


Fig. 44. Pelton Wheel, Showing Bucket Construction

grade. Improvements in efficiency and in the design of turbine settings still leave much to be desired.

Types of American Water Wheels. — The Pelton water wheel shown in Fig. 44 is of the impulse type, and operates by direct pressure. It is constructed in its simplest form of a cast iron or steel center, to the periphery of which are attached tangential vanes or buckets. The illustration

shows the standard type wheel mounted in a wooden frame, and clearly shows the bucket construction, the nozzle, and gate valve. The buckets are constructed of steel, phosphor bronze, or cast iron, as the conditions may require. The wheel centers are made of steel and cast iron, and for very high powers are of the disc type. The wheels are driven on the shaft by hydraulic pressure and rigidly keyed. Bearings are of the ring-oiling type, the barrels being lined with a special babbitt metal.

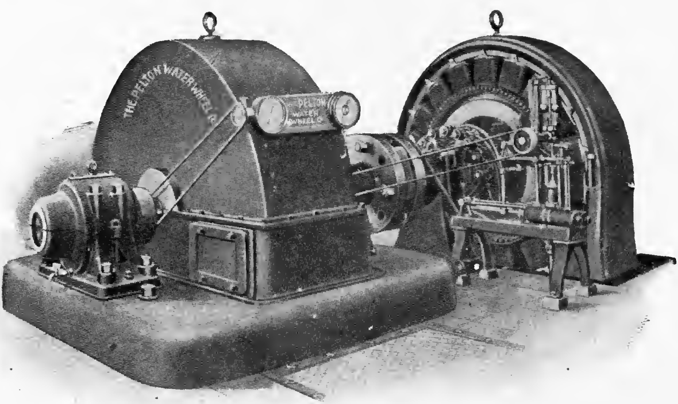


Fig. 45. A 3,000 Horse-Power Pelton Wheel Direct Connected to Generator

The housings of the wheel are usually constructed of sheet steel or cast iron, riveted and caulked, and have cast iron planed flanges for joints. In order to prevent leakage of water along the shaft and into the journals, a device known as a "centrifugal disc" is employed. It consists of a cast iron disc attached to the shaft of the wheel and revolving within the wall chambers, being secured to the interior of the wheel housing. Water collecting on the

shaft is caught by the disc and thrown into the centrifugal chamber, from which it is drained away through a tube into the tail race.

The Pelton wheel is also designed for several nozzles, in order to increase the power of the wheel without proportionately increasing its diameter. The wheel is constructed with a free discharge, in order to prevent leaves, trash, or matter in suspension from choking up the buckets.

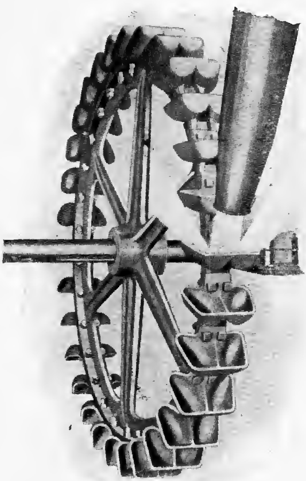


Fig. 46. Bucket Construction of Risdon Wheel

Fig. 45 shows a 3,000 horse-power Pelton wheel of the iron-mounted type, direct connected to a 1,500 kilowatt generator through a leather link coupling.

The runner of the Risdon wheel made by the Risdon Iron Works, San Francisco, is shown in Fig. 46, which also shows the bucket construction employed. The vanes are of the tangential form, and designed to prevent the water from reacting from a bucket in a way which will cause it to strike against a succeeding bucket. The water is thus deflected in a clear and free direction. The buckets are made interchangeable, and are bolted to the rim or center by heavy, square-headed bolts with lock nuts ; each bucket bolting closely with dovetails to the one on each side of it, thus making a continuous ring when all are placed in position. Buckets of different size may

be adapted to conform with nearly every size or diameter of wheel, so that the proportion of revolutions to power may be designed to suit various conditions of operation.

Fig. 47 illustrates a 3,000 horse-power, double unit Risdon wheel for direct connection to an electric generator. The unit consists of two wheels of disc form, eight and a half feet in diameter, mounted on the same shaft, each wheel being driven by a single jet, at 240 revolutions per minute. The buckets and centers of the wheels are made of cast steel. Bucket wings are milled out on an Ingersoll

Fig. 47. Double Unit 3,000 Horse-Power Risdon Wheel

slabbing machine, and driven on the edge of the turned disc. Through wings and disc, holes are drilled to template, and fitted with driven-in, turned steel forged bolts.

Under normal load the bolts securing the buckets to the periphery of the wheel may be under a strain of 65,000 pounds each. To obviate any danger from this source, it is claimed that the bolts are each made to undergo a strain of 700,000 pounds without breaking, or at normal load, the bolts have the exceedingly high factor of safety of sixty. The discs on which the buckets are mounted are bored

and shrunk on a heavy shaft, the factor of safety of which against torque and weight is claimed to be over fifteen.

The bearings are of the adjustable, ring-oiling ball and socket type, with very large surfaces, which are lined with anti-friction metal.

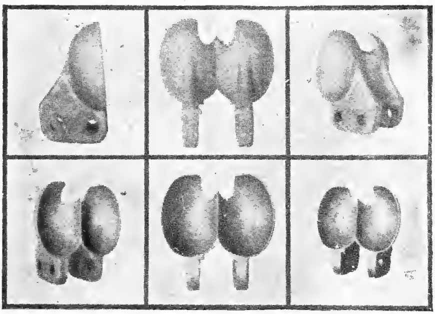


Fig. 48. Bucket Construction of the Doble Wheel

The Doble Water Wheel.—The Doble wheel, made by the Abner Doble Company, of San Francisco, is also of the tangential ellipsoidal type. Fig. 48 shows the bucket construction of the wheel, and Fig. 49 shows the runner of a 3,700 horse-power wheel designed for operation under a head of 1,531 feet. The wheel proper or body is constructed of a nickel steel forging, 10 feet 5 inches in diameter, and weighing over 10,000 pounds. The buckets are made of open-hearth steel castings, and are designed for a jet of water four and a half inches in diameter. Each bucket is fastened to the periphery of the wheel by two fitted bolts in reamed holes.

Fig. 49. Runner of 3,700 Horse-Power Doble Wheel

The nozzle used on the Doble wheel is of the needle-regulating type; the adjustment being effected by moving a core axially within the nozzle, thereby varying the annular area of the orifice. Fig. 50 shows a jet issuing from a needle-regulating nozzle under a high head.

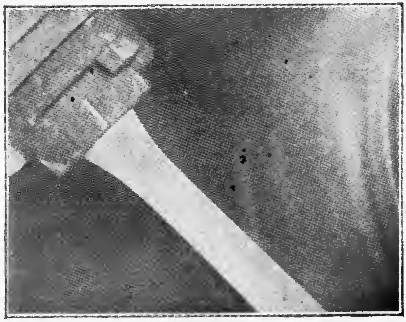


Fig. 50. Needle-Regulating Nozzle

Accessories of Turbines and Water Wheels. — In regulating the supply of water to a hydraulic machine a gate valve or several gate valves are used. Such valves are arranged to work in a vertical plane by partially or entirely closing the admission orifice through the medium of a hand wheel or by means of gearing or rigging operated electrically or hydraulically.

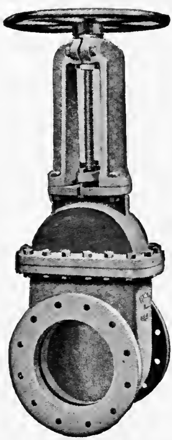


Fig. 51. A Straight-way Single Disc Gate-Valve

Various forms of gate valves are in use in American hydro-electric plants. Fig. 51 shows the Pelton gate valve. It belongs to the straight-way single disc type of valve, and is designed for pressure on one side

only. The spindle of the valve can be so manipulated by means of the hand wheel as to bring the disc entirely clear of the opening, thus allowing free passage-way for the water. When the valve is used on pipe systems in which the pressure is very high it is fitted with ball-bearings or some form of gearing.

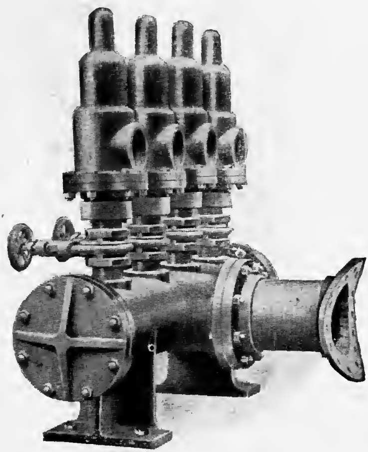


Fig. 52. Battery of Relief Valves for High-Pressure Pipe Lines

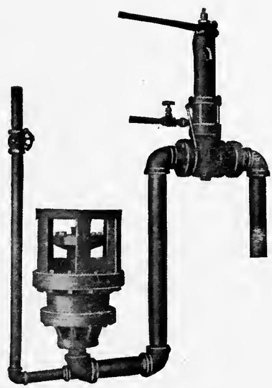


Fig. 53. The Lombard Water-Balanced Relief Valve

Safety Relief Valves become necessary on pipe or conduit systems working under very high pressure. They are generally placed at the lower end of the pipe line, in close proximity to the nozzle. Their operating pressure slightly exceeds the normal working pressure, and in case of a sudden stopping of the water flow by the closure of the gate valve or some accident to the governor, the safety valves open for an instant to relieve the pressure. This safeguards the pipe system against the serious dangers

resulting from water hammer. If the pipe line is of very large size and the pressure extremely high, a battery of safety relief valves is used. Fig. 52 shows a battery of such valves, made by the Pelton Wheel Company.

Fig. 53 shows the Lombard water-balanced relief valve. In this type of safeguarding appliance the pressure of the water against the gate valve is opposed by the hydrostatic pressure at the point where the valve is fitted to the flume or casing of the wheel. The valve remains closed so long as the operating pressure does not exceed the static pressure. But when the normal pressure is exceeded in the flume the valve at once opens and discharges water until the pressure is restored to the normal condition.

Fig. 54. Mechanically Operated Gate Valve

Fig. 54 shows a Ludlow high-pressure valve of the double-gate type, constructed of iron and bronze. The valve is operated by means of bevel gearing, the position of the gates being adjustable with center bearings to prevent the sticking of the parts. The type shown is fitted with an indicating device to show the position of the gate, and also a by-pass outlet.

BIBLIOGRAPHY

Mechanics of Engineering. Volume 2. Hydraulics and Hydraulic Motors. Weisbach-Du Bois.

The Theory of Impulse Wheels. Kingsford. *Engineering News.* July 21, 1898.

Turbines. Wood. Second Edition. Wiley & Sons. New York. 1901.

The Need of Turbine Standards of Measurement. Replogle. *Engineering News.* October 23, 1902. Page 339.

Water-Wheel Regulation. Garrett. *Cassier's Magazine.* New York. May, 1901.

Report of a Turbine Test. Webber. *Engineering News.* New York. April 20, 1903. Page 386.

Tangential Water-Wheel Efficiencies. Henry. Transactions Pacific Coast Electric Transmission Association. June 16, 1903.

Modern Turbine Practice and Water-Power Plants. Thurso. D. Van Nostrand Company, New York. 1906.

CHAPTER IV

GENERATORS, SWITCHES, AND PROTECTIVE DEVICES

Kinds of Generators Used. — Three distinct types of alternating-current machines are used in generating current for long-distance transmission, namely, the revolving armature generator, the revolving field generator, and the inductor generator. Of these types the revolving field generator is most used, and is rapidly supplanting the other two types.

The revolving armature alternator is generally used in outputs up to 800 kilowatts. The field magnet of this type of machine is constructed of either laminated or solid steel, either cast into the frame of the machine or bolted to it radially. In some few cases cast-iron poles are used. The magnet coils are in nearly every case form wound on collapsible mandrels, and the conductor is copper wire, bar, or strap, depending on the output of the machine. Field magnet coils are insulated with oiled muslin or linen, fuller board, micabeston, vulcabeston, etc., and the separate layers are sometimes protected by coatings of shellac.

The armature of this type of generator is generally drum or barrel wound, and the core is usually of the toothed type. The armature coils are almost invariably form wound and of substantially rectangular outline; in machines of considerable output the conductors are copper

straps or bars, each insulated from its neighbor by layers of fiber impregnated with a bituminous compound and varnished with a heavy coating of shellac, or by micanite and oiled linen, or some similar combination.

The separate conductors belonging in one slot are assembled into a bundle and tightly bound together with insulating tape coated with a moisture-proof compound. The bundles of bars are then laid in the slots around the periphery of the armature coils, which are insulated by troughs of insulating material; after the coils are secured in place they are connected up to each other and the complete winding is connected to the "collector rings."

The revolving field generator is built in two general forms: one in which the field magnet surrounds the armature, as in the case of the Niagara Falls machines, and the other in which the armature surrounds the field magnet; the latter is the more generally used. External field machines with revolving magnets are used only in special work, such as that at Niagara Falls. In construction they are generally similar to revolving armature machines, except that the shaft is usually vertical, for coupling to a water turbine, and the field magnet is of the overhung or umbrella type.

The revolving field generator with the armature surrounding the field magnet comprises an annular armature core, mounted in a cast-iron housing, and a wheel or spider mounted on the shaft and carrying radial field magnet poles on its periphery. The armature winding is laid in slots around the inside of the armature core. In machines of large output this mode of construction has much to recommend it, its especial advantage being that with a given peripheral speed of the moving element there is more

room for the disposition of the armature coils. Moreover, since the coils are stationary, they admit of a higher degree of insulation than is possible with moving windings.

The frame of the revolving field type being provided with air ducts, the rotating field maintains a better circulation of air through the coils than is the case with the stationary field type. The absence of moving contacts for taking off currents of large value is also highly advantageous. The only moving terminals are those for establishing connection with the field winding, and which have to carry but small currents at low voltages.

The Inductor Generator. — In this type both field and armature windings are stationary, the rotating member consisting of bare, soft iron fitted with projections termed "inductors." The projections receive their magnetization from an annular field coil, which also magnetizes the stationary part of the magnetic circuit. The frame surrounding the inductor has radial projections which correspond to the inductors both in number and proportions, and on these are mounted the generating coils. (See Figs. 56*a* and 56*b*.)

When the inductors in rotation come immediately opposite to the faces of the stationary poles, the magnetic reluctance is at its lowest value, consequently the flux through the generating coils is at its maximum value. Conversely, when the inductors are at intermediate positions, the magnetic flux interlinked with the generator coils is smallest, and consequently the E.M.F. is at its lowest value.

Hence, at the various polar points around the frame of the generator the flux is varying from maximum to minimum, and back again, but does not alter its direction or polarity.

Inductor generators are wound to deliver single and polyphase currents, the armature windings being usually of the concentrated type. It will be apparent from the shape of the pole pieces that the instantaneous value of the E.M.F. in a coil is proportional to the strength of the magnetic field which it is cutting at that instant. Hence, with a fairly uniform magnetic density over the pole face, the curve of instantaneous E.M.F. during a cycle will not be a sine curve, but a flat-topped curve with an abrupt approach to a zero value.

An approximate sine curve in an inductor generator may be obtained by a distribution of the windings in two or more slots per pole per phase, or else by such shaping of the pole faces as will vary the density in the air gap, so as to carry the E.M.F. wave up gradually instead of suddenly.

Since all the poles on one side of the inductor generator have the same polarity, the magnetization of the armature teeth and iron is approximately in the same direction.

The advantages claimed for the inductor generator are, that the iron is worked through only half a cycle, which makes the iron losses quite small, if the machine is worked at low magnetic densities; freedom from moving wire, which reduces the liability to breakdown by the chafing of insulation; ample space for insulation, due to stationary wire; absence of moving current-collecting devices, and hence no losses due to sparking and brush friction.

The Regulation of Generators. — The inherent regulation of an alternating-current generator is usually defined as the percentage rise of voltage when the total non-inductive load is thrown off, both generator speed and field excitation being kept constant.

According to the Standardization Committee of the American Institute of Electrical Engineers, "The regulation of an apparatus intended for the generation of a potential, current, speed, etc., varying in a definite manner between full load and no load, is to be measured by the maximum variation of potential, current, speed, etc., from the satisfied condition under such constant conditions of operation as give the required full load values."

In apparatus which transforms, generates, or transmits alternating currents, regulation refers to non-inductive load, *i.e.*, load in which the current is in phase with the E.M.F. at the outside of the apparatus, and is expressed in percentage of the full load value.

The inherent regulation of standard American alternators varies from sixteen per cent to six per cent on non-inductive load, depending on the output and type of machine.

On inductive load the regulation of standard machines varies from twenty to ten per cent according to the output and the kind of machine.

The fundamental factor involved in securing high inherent regulation in a generator is good inductive load regulation, which means the use of large amounts of copper and high magnetic densities in the iron. High inherent regulation is obtained at the expense of output per pound of material.

Generators for long-distance power transmission work should have good inherent regulation, because machines under such conditions of operation cannot be compounded, for the reason that compounding would only compensate for the losses at one definite power factor.

Moreover, in the majority of high-tension stations the machines are worked in parallel, in which case compounding becomes impractical.

Efficiency of Generators. — The efficiency of an alternating-current machine is the ratio of its net power output to its gross power output. The determination of the efficiency of an alternator is made by measuring the electric power when the current is in phase with the E.M.F., unless otherwise specified.

In case a generator has an exciter or other auxiliary apparatus the power consumed by the auxiliary apparatus should not be charged to the machine, but to the entire plant comprising machine and auxiliaries taken together. Plant efficiency is then to be distinguished from machine efficiency.

Efficiencies of generators used in long-distance power plants vary from 90 to 97.5 per cent (at full load). Fig. 55 shows the Several ~~efficiency~~ curves of an 1,850 kilowatt machine. The table below gives efficiencies of several Bullock generators.

LOAD.	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$	1	$1\frac{1}{4}$	$1\frac{1}{2}$
AK 14–9,015¾, 1,000 kw., 11,000 v., 257 rev......	86.	92.2	94.2	95.2	95.7	96
AK 18–7,517, 1,200 kw., 2,300 v., 400 rev........	87.	93.	95.	96.	96.6	
AI 50–180 14¾, 1,500 kw., 2,400 v., 120 rev	87.8	93.4	95.	96.	96.5	96.7
AK 26–130–20, 2,000 kw., 2,200 v., 231 rev.......	87.4	92.9	95.	96.	96.5	96.9
AI 96–36,011, 2,500 kw., 4,500 v., 75 rev.........	90.	94.2	95.6	96.3	96.6	96.8
" " 3,000 kw., 4,500 v., 75 rev	91.	95.	96.2	97.	97.4	97.6
AK 16–6,519, 800 kw., 2,300 v., 450 rev..........	85.	91.5	94.	95.	95.5	95.7
AK 36–1,207¾, 750 kw., 2,400 v., 200 rev	86.	92.	94.2	95.	95.4	95.4
AH 18–7,512, 600 kw., 2,400 v., 400 rev...	80.	89.	92.	93.5	94.3	95.
AI 60–1,807, 400 kw., 2,400 v., 120 rev..........	80.3	88.6	91.7	93.2	94.	94.3

Parallel Operation of Generators. — The parallel operation of generators in hydro-electric plants is absolutely essential to economical operation in cases where large powers are

developed, in order to reduce the number of circuits and transmission lines. Generators of standard make and proper design, coupled to water wheels, operate in parallel

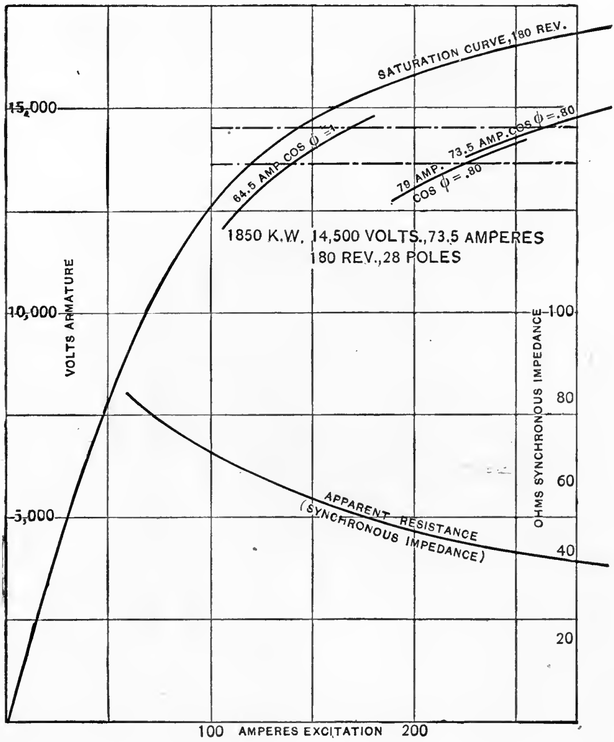


Fig. 55

with absolute reliability and simplicity, because of the perfectly uniform angular motion of water wheels.

The most important requirement of a generator intended for parallel operation is a reasonable amount of armature reactance. If the reactance is too small, an enormous

exchange of current between the machines is liable to occur when there is even a slight difference in their field excitation, or if the machines are thrown in parallel when there is a slight phase difference between them. Parallel operation of machines with an excessive amount of armature reactance can also be effected, but their operation

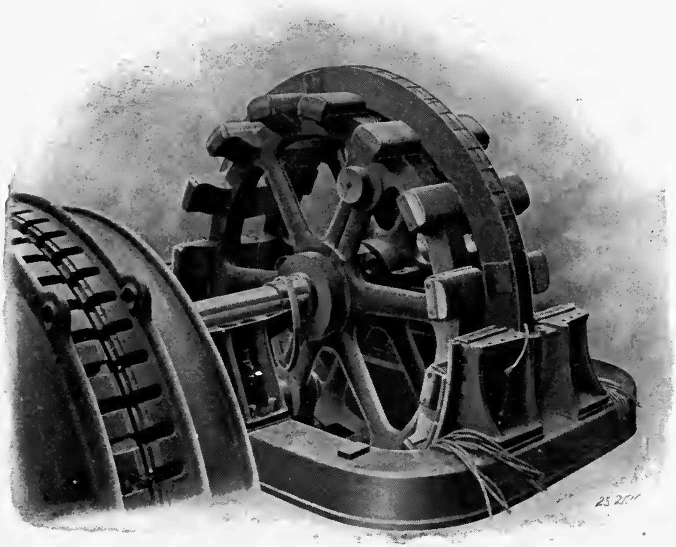


Fig. 56*a*. Construction of 2,000 K. W. Water-Wheel Type Inductor Generator

under such conditions is not stable, and "hunting" frequently occurs, due to the exchange of a small synchronizing current between them.

In cases where a number of generators are operated in parallel the field excitation of each machine is individually adjusted to enable it to supply its share of the total

current, which prevents an exchange of current between the machines.

The fly-wheel effect obtained from the large masses of metal in revolving field generators conduces greatly to stability of operation in parallel, and tends to produce uniformity of angular motion.

Figs. 56*a* and 56*b* show a 2,000 kilowatt high-speed

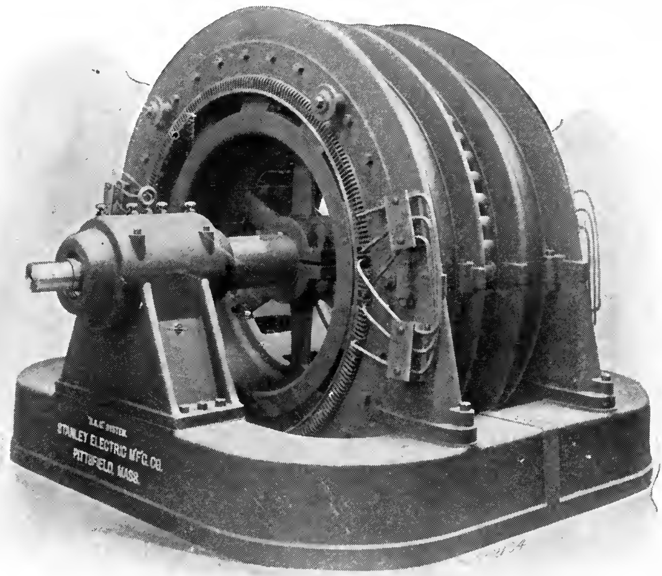


Fig. 56*b*. A 2,000 K. W. Water-Wheel Type Inductor Generator Completed

water-wheel type inductor alternator, made by the Stanley Electric Manufacturing Company. The stationary part of the machine nearest the air gap is built up of laminated iron, the coils being wound and insulated separately and laid in slots in this part, in the shape in which they are wound.

The single field coil is stationary and is form wound on a brass spool from which it is thoroughly insulated. The secondary action of the brass spool tends to obviate danger from the breaking down of the insulation of the coil when the field circuit is broken.

The revolving part consists of bare cast steel, keyed to the shaft, and is filled with laminated iron projections or

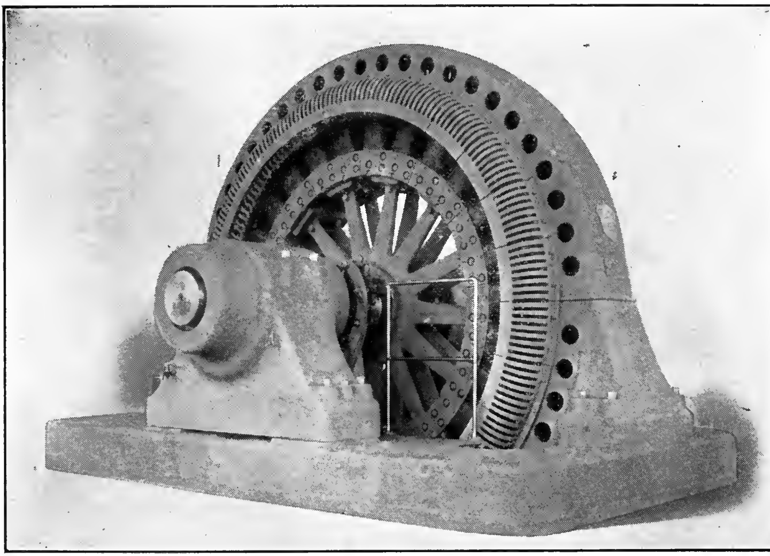


Fig. 57. A Bullock 3,000 K. W. Water-Wheel Type Generator

inductors on its surface. The bearings are of the self-oiling, self-aligning type.

Fig. 57 shows a 3,000 kilowatt, 4,400 volt, 3 phase, 60 cycle Bullock revolving field generator of the water-wheel type. The armature is built up of mild annealed steel of high permeability, the laminæ being japanned to reduce

eddy currents. The armature coils are wound on cast-iron forms, the conductors being carefully insulated from each other and from the core.

The field coils are constructed of copper strap bent edgewise. The difference of potential between the turns is but a fraction of a volt, which insures freedom from insulation breakdown. The bearings are of the self-adjusting, self-oiling type.

Fig. 58 shows a 3,750 kilowatt water-wheel type Westinghouse revolving field generator. The illustration shows the machine during erection in a hydro-electric plant. The field magnet is constructed of laminated steel punchings fastened together by bolts and dovetailed into a cast-iron spider. This spider does not form a part of the magnetic circuit, the lines of force going only through the laminations. The construction is designed to give the rim sufficient strength to resist the strains caused by centrifugal force without straining the central spider. The field magnet coils are form wound with copper strap bent on edge. Wedges of copper serve to retain the coils in place and also act as "dampers" to reduce the shifting of the flux across the pole faces due to armature reaction.

The armature is built up of slotted steel punchings dovetailed within a cast-iron frame. The winding consists of copper strap bent into the required shape and held in open slots by hard fiber wedges.

Switchboards for High-Tension Current. — The switchboard being virtually the heart of a transmission system, its design and equipment are of vital importance in the safe and trustworthy operation of a plant.

Switchboards for high-tension plants are made of care-

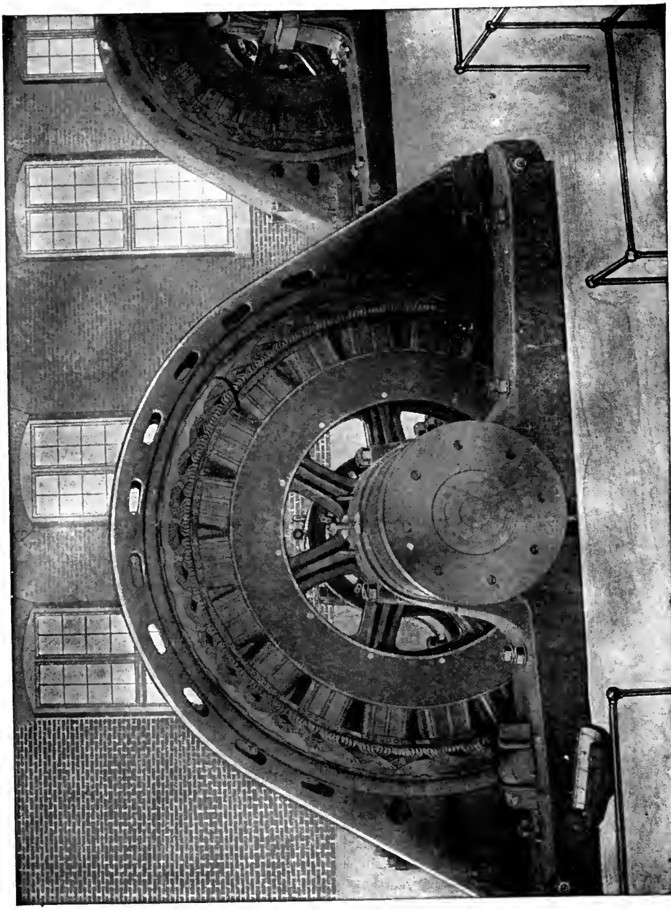


Fig. 58. A Westinghouse 3,750 K. W. Water-Wheel Type Generator

fully selected marble and built up of panels, or units, which are bolted to structural steel frames.

The majority of high-tension boards in stations of large output are provided with a separate panel for each generator as well as a panel for each exciter unit; and in plants where two different pressures are generated there are generally panels for the feeders. A main junction panel in the middle of the board is sometimes provided by means of which it is possible to divide the board electrically into two parts, either of which may be closed down for repairs while the other is in service.

A high-tension generator panel is usually equipped with one or more circuit breakers; single-pole, double-throw main switches; two or three long-scale alternating-current ammeters; a dead-beat direct-current ammeter for the field circuit; a double-pole, single-throw, quick-break field switch, with shunt resistance and discharge attachment; series and shunt transformers; synchronizing devices; indicating and integrating wattmeters, etc.

In many cases the rheostats in high-tension stations are mounted under the gallery floor (or the main floor of the station), and are controlled by hand wheels on pedestals located directly in front of their respective generator panels.

On some high-tension boards there is provided a multiplying panel for duplicating the bus-bars. Multiplying panels are provided with a double-pole, hand-operated circuit breaker; single-pole, single-throw multiplying switches; a synchronizing device and double-throw switch for throwing the synchronizing device on any of the several sets of bus-bars.

Each panel for the raising transformers is usually

equipped with a single-pole automatic overload circuit-breaker, with time-limit relays; a long scale ammeter; a double-throw, double-pole main switch; lightning arresters and static interrupters, together with various auxiliary devices depending on the size of the unit. For each group or bank of transformers there is provided an integrating wattmeter and several shunt transformers.

In some high-tension stations the high potential board is arranged so that either of the two transmission lines may be operated on either bank of the transformers, so that either half of the switchboard may be "deadened" for cleaning or repairs while the other is in operation.

Switches for Handling High Voltages. — No apparatus employed in high-tension electric power transmission is of more vital importance than the switches used in controlling the circuits. The severe demands imposed on this part of the electrical equipment necessitate the highest skill and familiarity with the requirements which circuit-controlling appliances must fulfill.

Switches used in American high-tension practice are of several general types, namely, air-break switches, combined air-break switches and fuses, oil-break switches, combined oil-break switches and circuit breakers.

Oil-Break Switches. — For circuits operating under a pressure of a few thousand up to 60,000 volts, the oil-break type of switch has adequately demonstrated its reliability. A type of oil-break switch extensively used in plants of moderate pressure — *i.e.*, up to 15,000 volts — is shown in Fig. 59. It consists of two or three double-pole single-phase elements or switches (the number depending

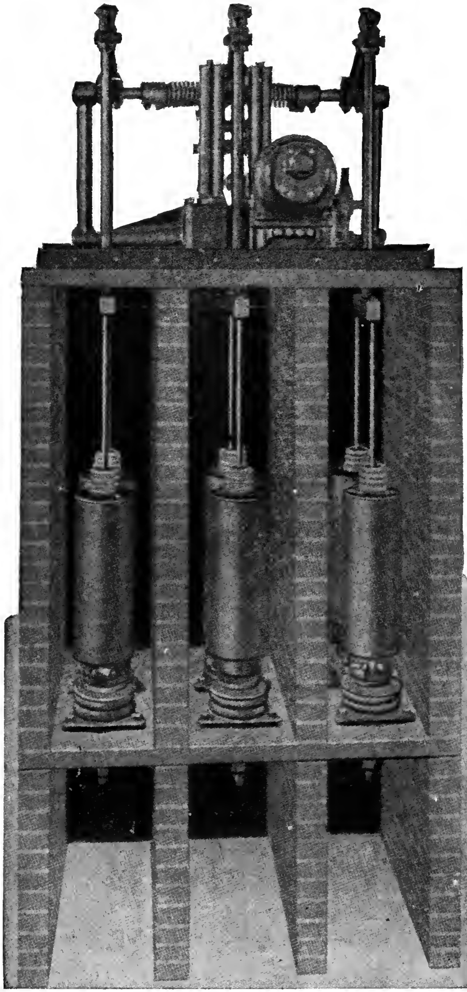


Fig. 59. Oil-Break Switch for Moderate Pressures

on whether the circuit is two phase or three phase) inclosed each in a fire-proof cell, but arranged for simultaneous operation. Each element of the switch is usually made up of two brass cylinders, one cylinder per pole. The incoming terminal of one phase is attached to one cylinder, and the outgoing terminal of the same phase to the other cylinder. Each cylinder is filled about two thirds full of oil and is covered over with a metal cap, to which is attached a long insulatingsleeve. Two copper rods forming vertical spindles and united by

a metallic cross-head at the top slide through the insulating sleeve and fit into tubular contacts at the bottom of the cylinder when operating to close the circuit. To the

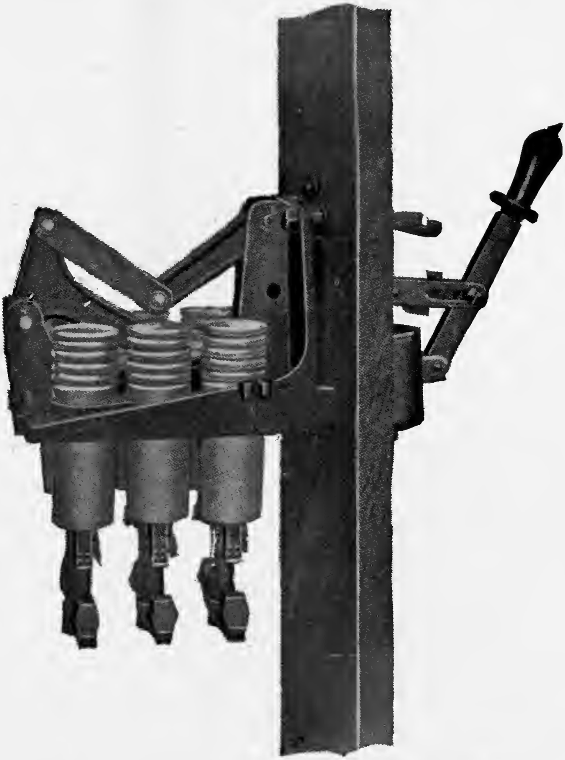


Fig. 60. Type of Oil-Break Switch for High Pressures

cross-head of the copper rods is attached a wooden rod extending through the top of the cell which incloses the switch. This rod is attached to a metallic cross-head, which is actuated by either electric or pneumatic devices.

When the rod conductors of the switch are raised the

circuit is broken under the oil in two places in each phase. The range through which the cross-head can be actuated varies with the pressure which the switch has to handle. In order to keep the arc from jumping from the copper rod to the cylinder when it is drawn through the oil, the cylinders are lined on the inside with fiber. The isolation of the composite poles of the switch in separate fireproof compartments is to prevent a burn-out in one cell from spreading to the others, and thus causing a complete breakdown of the switch.

Another type of oil switch in successful operation on high-tension circuits is shown in Fig. 60. The switch mechanism comprises two or more metallic contact pieces depending upon whether the switch is of single, double, or triple pole type. The contact pieces are attached to separate rods of chemically treated wood, which in turn are attached to a cross-head actuated in a vertical plane by a system of levers. Each contact piece makes electric connection by means of a clip, which is supported from the frame by porcelain insulators, so as to insulate all live parts. When the contact pieces are brought to their upper position, the switch is closed. On opening, the contacts fall into the bottom of the oil cylinder.

The live parts of the switch, such as clips, contact pieces, etc., are entirely immersed in oil when the cylinder is fitted in place. A switch of this type is not intended to break loads under extreme emergencies, such as a short circuit just beyond the switch on the load side. Nor is its use advisable directly on panels which in extreme instances can exceed 2,500 kilowatts, three-phase, or 1,500 kilowatts, single-phase power. Under such conditions, single-pole, single-phase switches of the type shown in Fig. 59 are

generally employed. The type of switch here shown is automatic in its operation and is designed to perform all of the functions of a circuit breaker. Two kinds of

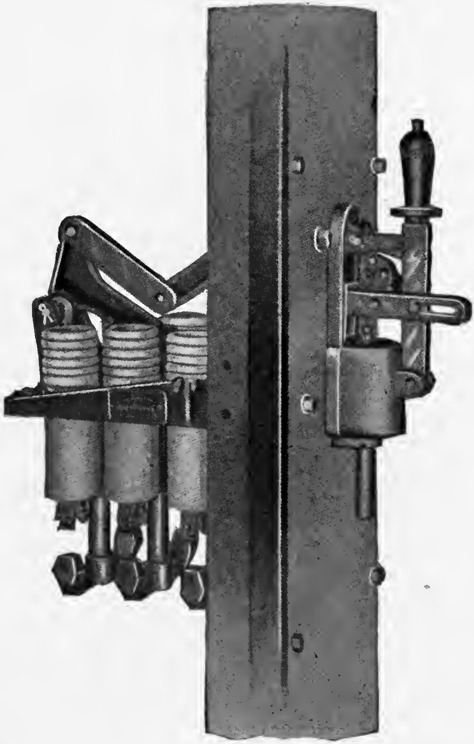


Fig. 61. Switchboard Tripping Mechanism of Oil Switch

mechanism are used to actuate it, these differing from each other according to whether the switch is mounted directly on the switchboard or is placed in cells at some distance away. The mechanism of the first or the switchboard tripping mechanism is shown in Fig. 61. It

is made up of a series of coils placed on the face of the board and energizing armatures which operate to release a latch on the interconnecting link between switch and handle. Connected in series with the main switch are the secondaries of current transformers which energize the coils of the tripping device. When the switch is automatically opened by this tripping device, the handle on

Fig. 62. Portion of Circuit Breaker on Face of Switchboard

the face of the board remains closed, and the link moves forward through the handle, giving unmistakable indication that the switch has automatically opened.

Combined Oil-Break Switch and Circuit Breaker. — A radically different type of oil-break switch with attached circuit breaker is shown in Figs. 62 and 63. Fig. 63 shows the portion of the switch behind the board. Fig. 62 is

an illustration of the portion of the mechanism which is on the face of the board. Each pole of the switch is immersed in oil in a separate compartment lined with procelain; the object of this arrangement being the prevention of current leakage and short circuits from pole to

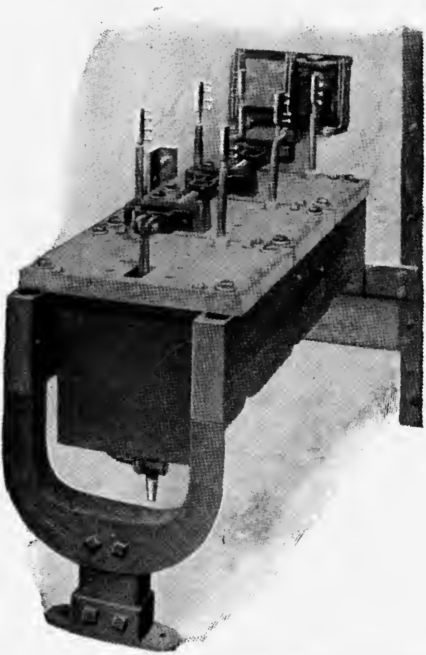


Fig. 63. Portion of Circuit Breaker Behind Switchboard

pole. Each contact is tipped with zinc in order to obviate pitting action on the blades. By means of the four screws fitted in the marble cover of each compartment of the switch the tank may be removed without disturbing the switch mechanism, even while it is carrying current.

This form of oil switch is used in either the single or

double throw type with single, double, triple, or quadruple poles. Its capacity ranges from 4,000 volts and 1,000 amperes to 15,000 volts and 100 amperes. The circuit-breaker attachment is operated by means of the disc shown at the lower part of the illustration, Fig. 62. The circuit breaker is adjusted to open at different loads by setting the dial hand at the points corresponding to the loads.

Air-Break Switch with Fuse. — A very ingenious air-break switch, with fuse attachment, is shown in Fig. 64. This type of switch is in use in the plants of the Bay Counties Power Company and the Standard Electric Company, of California, and deals with potentials as high as 60,000 volts.

The elements of the switch consist of a main arm, an auxiliary arm, a fuse holder, and two contact pins. The main arm consists of a wooden rod hinged at the lower end to a bracket mounted on the switchboard. On the top of the main arm are mounted two zinc jaws which hold one end of the fuse. The arm also carries two blades which make contact with the terminal jaws. The blade near the free end is electrically connected to the zinc jaws, while the lower one is connected by means of a cable to the auxiliary arm.

The auxiliary arm is a hollow wooden rod hinged at its lower end to the main arm.

Attached to its free end are two zinc plates forming the holders for the other end of the fuse. A copper rod attached to the auxiliary arm forms the connection between these plates and the cable which connects the lower blade on the main arm.

In the event of the fuse becoming unlatched or blowing

out, the auxiliary arm is quickly pulled, the jar of its fall being absorbed by a dash pot attached by a bracket to a main arm.

The fuse holder comprises a hollow insulating tube fitted at each end with perforated corks, and filled with a non-fusible and non-conducting powder through which the fuse is drawn. When it is not supported by the fuse it is tied to the main arm in order to prevent its falling out of position. The fuse is maintained in its position between the main and auxiliary arms by the zinc jaws on the top end of the main arm and the zinc plates on the auxiliary arm.

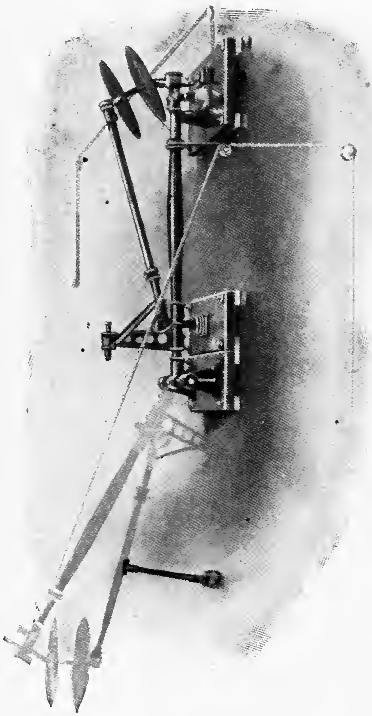


Fig. 64. A High-Potential Air-Break Switch

The jaws which form the terminals are carried by separate blocks of marble, and are further insulated from the marble of the switchboard by means of porcelain strips and bushings. There is also mounted on the upper marble blocks the latch which opens the zinc jaws on the main arm. This latch is operated to release the fuse by means of the rope shown in the engraving.

The operation of the switch to rupture a loaded circuit is as follows: With the switch in its normal position, current is led to the upper terminal, passing thence to the zinc jaws on the main arm, from which it passes through the fuse to the auxiliary arm, down the auxiliary arm, and through the cable to the lower blade on the main arm; thence it passes out through the bottom terminal. A pull on the latch rope forces the jaws open and thereby releases one end of the fuse, which is then rapidly drawn through the non-conducting powder in the holder tube by the fall

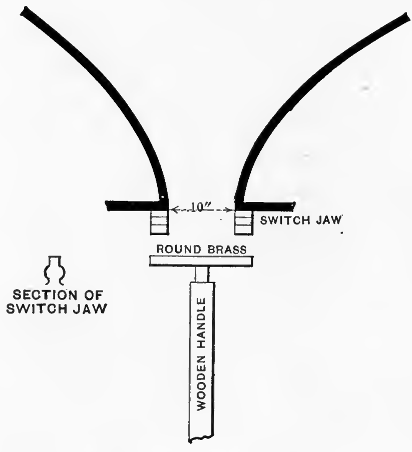


Fig. 65. A "Ram's Horn," Pole-Line Switch

of the auxiliary arm to its horizontal position, thus rupturing the circuit and blowing out the arc which is formed. The main arm is then unlocked from the catch, and the mechanism of the switch swung down to an accessible position, and the fuse replaced. When this is accomplished, the mechanism is returned to its normal position by means of

the rope on the main arm. In order to prevent the fuse from rupturing under medium load and instantaneous overloads, it is made heavier than it would be were the device intended for automatic fuse action rather than a switch.

Air-Break Switches. — In many long-distance transmission plants in the West the high-tension switches employed are simply long-break "stick" switches in which the length of the break is depended on for opening the line. A common home-made switch of this kind has an inclosed fuse attached to the stick on which the switch jaw is carried. When the fuse is blown the switch stick is pulled out and replaced by a similar fused stick, as in the case of an ordinary low-tension removable fuse holder.

Another type of home-made switch contains a short fuse mounted between carbon blocks under more or less tension. When the fuse is blown or when a trigger device which holds the switch closed is tripped, the blocks are instantly thrown apart.

These types of combined stick switches and fuses are generally made interchangeable so as to admit of easy replacement.

A type of switch largely used in Pacific coast high-tension practice is a "ram's horn," air-break, pole-line switch. Fig. 65 illustrates a switch of this kind which has proven quite reliable in handling a potential of 33,000 volts. The jaws of the switch are placed side by side, only thirteen inches apart. Just above the switch-jaws are two curved conducting strips made of line wire. The switch jaws are normally connected together by means of a cylindrical brass rod, attached to a long wooden handle. The jaws have a bayonet clip on their ends which engages

the brass rod and prevents it from falling out when the switch handle is released.

When the circuit is broken by pulling the brass rod out of the switch jaws by means of the attached handle, the arc which ensues is blown up between the horns by the heated air currents until it passes the point where its length is the maximum that the voltage behind it will maintain, and it breaks.

Conditions which Render Switching Necessary. — A careful consideration of the conditions under which it becomes imperative to open high-tension transmission lines will lead to the conclusion that such instances are indeed few. The opening of high-voltage lines on the high-tension side of transformers is one of the most fruitful causes of trouble in the operation of transmission lines. Hence, for very high pressures, switching either should not be done at all or, if it must be done, it should be accomplished on the low-voltage side of transformers. There is, however, one catastrophe which renders it unavoidable. If a transformer is in any way set on fire, and it becomes necessary to cut it out without bringing about an interruption of service, the high-tension switch must be opened regardless of line conditions. It is for such infrequent emergencies that a stanch and trustworthy switch is most needed.

The major part of the switching done under load can be equally well carried out from the low-voltage side of transformers as from the high-tension side. The most common switching operation is that of cutting out a bank of transformers. This operation can be best done first on the low-voltage side, thus leaving only the transformer exciting current to be cut off on the high-voltage side. In most

cases it is better to leave the transformers in circuit rather than break the high-tension side under no load. In the event of a persistent short circuit on the high-tension line, it is quite feasible, and generally best, to break the low-voltage circuits first.

Automatic Station Protective Devices. — Perhaps no part of the subject of long-distance transmission has received more attention than the protection of high-voltage apparatus from damage due to abnormal conditions. The proper design and installation of protective appliances is a matter of far-reaching importance in the laying out of a high-tension line, since the insertion of safety apparatus at the proper point in the line will obviate an endless amount of trouble.

The several kinds of protective appliances used in high-tension practice are fuses, circuit breakers (either separate or as composite parts of oil-break switches), overload relays, time-limit relays, and reverse-current relays. Of these widely different devices, as regards the function each is designed to exercise, the fuse is the simplest means for automatically breaking a circuit.

Fuses for high-tension alternating-current circuits are quite different from those in use on direct-current lines, for the reason that when a fuse ruptures on a high-potential circuit, the arc that is drawn tends to persist, owing to the high voltage behind it. The current of a high-potential line thus ruptured tends to maintain the continuity of the circuit by following the path of the heated air; it may also jump to a point on the other side of the line, and short circuit the line between the protective device and the source of supply. The one object in common in the various kinds of fuses used in

alternating-current practice is thoroughly to insulate the fuse from the neighboring parts of the line. Thus it is intended that the suppression of the arc shall be from the fuse block into the neighboring air, thereby increasing the length of the break, and so effectively opening the circuit.

Fuse blocks are generally mounted on the back of the switchboard, either on separate marble bases or near the top, and are rigidly secured to the board by means of brackets on the rear of the board.

A type of fuse holder in use on alternating-current circuits not exceeding 2,500 volts in pressure is called an expulsion-block fuse, Fig. 66. It consists simply of a porcelain block in which a rectangular hole has been cut. This recess receives a block of lignum-vitæ. At each end of the porcelain block there is fitted a copper stud, which extends through the upper surface and is an elongation of the chisel-shaped contact piece. These also hold the cover of the block in place, which is likewise made of

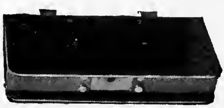


Fig. 66. A Type of Lignum-vitae High-Tension Fuse Block

lignum-vitæ and fitted with an air-vent, and well insulated by thumb-screws on the studs. The fuse is placed under the vent in the upper lignum-vitæ block and between the two, and is joined to the copper studs. When the fuse blows the arc takes place between non-combustible material, and hence is blown upward into the atmosphere.

When the potential of the circuit exceeds 2,500 volts, a mechanical device is used to sever the fuse when the tensile strength is reduced by the heating produced by overload currents. Rupture of the circuit just before the fusing point is reached reduces the current of hot air bridging the gap, and consequently tends to suppress the ensuing arc. The tendency to emit showers of fused metal is also overcome, and a quicker breaking of the circuit is made possible. The mechanical means adopted to produce this result consists of a spring-expulsion fuse block introduced in the circuit in the same way as the expulsion block already described. It is made up of a base and two side pieces of hard wood, the whole being varnished and fireproofed. On the base is fitted a lignum-vitæ block, which goes between the terminals of the circuit. The fuse block is connected to the circuit by means of a chisel-shaped piece, similar to those used in above-described fuses. Each piece goes through the base, and is attached by means of copper strap to a copper plate. The copper plate has mounted on it a stud with a vent and washer, and is in the shape of an inverted U; the two ends being carried on a pin which rotates in the plane of the chisel piece. A stout spring mounted on the pin holds the copper pin normally in a recumbent position on the base of the block. The set fuse rests on the lignum-vitæ block, and is long enough to hold these terminals in a vertical position. Such a fuse is stout enough to overcome the tendency of the terminals to spring back on the base, but when its tensile strength is diminished by heating, the fuse quickly blows, as above described, and breaks the circuit. The current-carrying parts of the device are completely inclosed in fiber strips, and a cover of lignum-vitæ with an air vent is fitted over the

top. To obviate the tendency to arc over the sides, the side pieces are extended several inches beyond the inclosing strips.

When this fuse is used for potentials greater than 5,000 volts, the fuse-block connections are thoroughly insulated from the switchboard by tubes of molded rubber. These also support the block and the connections to the circuit behind the board and several inches from it. Expulsion-type blocks are in use to protect circuits operating under tensions as high as 20,000 volts and carrying 100 amperes.

Although the use of fuses is quite extensive on circuits of moderate voltages and currents, it becomes impracticable to employ them on high-tension circuits carrying large power. Under these conditions it becomes imperative to provide devices which will automatically open the circuit mechanically.

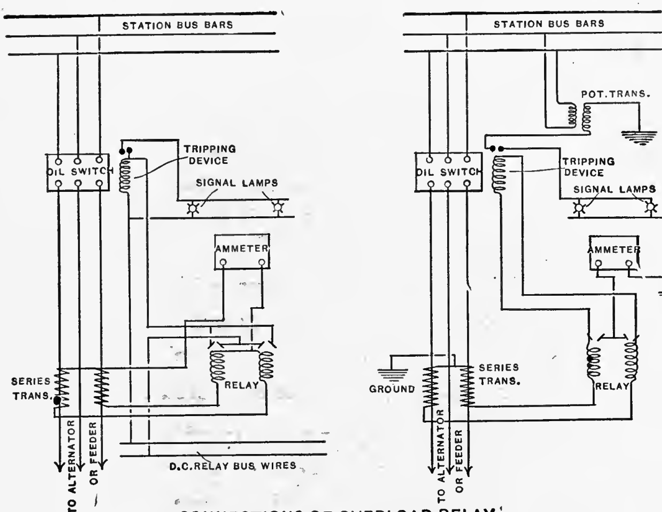
The overload relay is an apparatus which exercises a function similar to that of a circuit breaker. In its usual form an overload relay consists of a solenoid surrounding a soft iron rod or plunger, which is attracted upwards and causes an auxiliary bar to strike against contacts and close a local circuit, through the tripping magnet of an oil circuit breaker. In order to adjust the position of the plunger for varying current strengths it is supported by a disc in a tube which is fitted to the lower end of the solenoid. By adjusting the position of this disc vertically the plunger can be set to operate at any desired current strength.

In the event that it becomes necessary to use current from a single source, to actuate both the relay and the circuit breaker, which means current from the same transformer, the tripping mechanism on the oil switch is connected in series with the relay, and the secondary of the

current transformer. Normally, this connection short circuits the tripping mechanism, and the plunger of the solenoid in this case breaks the short circuit when it is pulled upwards, and so permits the operation of the tripping magnet.

The connections for both cases are shown in Figs. 67 and 68.

The overload time-limit relay is a device intended to



CONNECTIONS OF OVERLOAD RELAY

Fig. 67 Fig. 68

operate the circuit breaker, should the overload continue for some definite length of time, for which the relay has been set. Overload time relays are designed for two kinds of service, namely, to handle temporary or brief overloads, and to confine the effect of an overload to some local section of the circuit, and hence restore normal conditions by causing the protective appliance in that section to operate.

The first function it must discharge, sometimes, when lines become crossed or short circuited. In such cases the circuit often relieves itself, however, by burning out the obstruction, and it would be bad practice to open the circuit unless the trouble is prolonged.

When overload time relays are used on feeders or sub-feeders fed by an alternating-current generator, a very

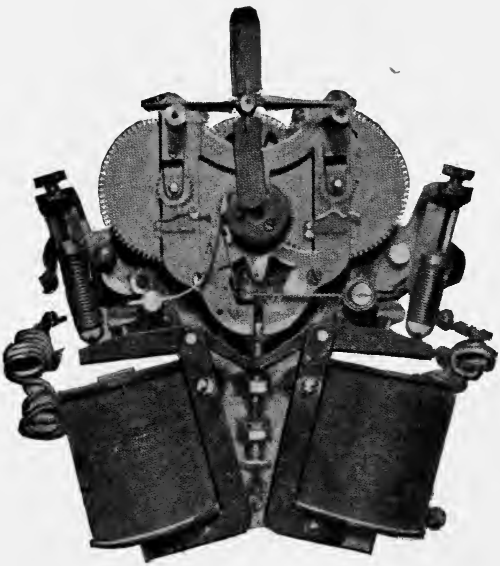


Fig. 69. Mechanism of a Time-Limit Relay

efficient method of protection is obtained by proper employment of the adjustable time feature. By using relays in the main feeders designed to open in, say, five or six seconds, relays in the sub-feeders which will open in two or three seconds, and instantaneously operating relays in

local circuits, an overload or short circuit in the main feeders would not be relieved unless it continued for the time mentioned; the same trouble would not be relieved in the sub-feeder for two or three seconds; while in the local circuit relief would occur instantly. Time-limit relays are operated by clockwork mechanism. Fig. 69 shows the mechanism of a time-limit relay. Fig. 70, two discs of wood, which are carried by slowly rotating shafts. Mounted on the periphery of each disc is a piece of copper strip, against which is pressed a contact piece of spring brass. A companion piece of brass is so fastened as to be just

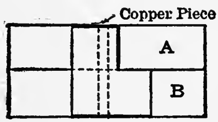


Fig 70. Detail of Time-Limit Relay

out of contact with the top of block *A*. On the shaft which carries the wooden discs is also mounted a notched brass wheel, which engages with a detent, presenting the movement of the clockwork. On a parallel shaft which revolves at a higher rate of speed are four aluminum vanes at right angles to each other; these are adjustable to vary the time interval by regulating the speed of the clockwork, which in turn controls the speed of rotation of the wooden discs. In most apparatus of this kind the time per revolution of the discs varies from three to ten seconds. The contact points are always connected in an auxiliary circuit, which generally carries a direct current at low pressure; they are in series with the tripping magnets of

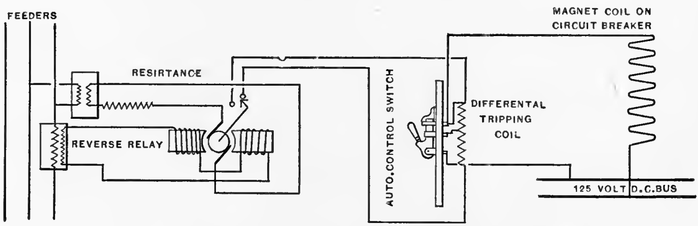
the oil-break switch, and therefore control the operation of that switch. Underneath a lever attached to the ratchet above mentioned is a cylindrical iron piece, about an inch in length, which is supported by a spring that has a vertical motion. Another similar iron piece and joined to it is mounted underneath the spring contact over the disc *A*. A solenoid which is excited by current transformers forces the two iron pieces upwards, whereupon one of them pulls down the ratchet. The iron pieces which are thus attracted by their cores are designed as levers. The time-limit relay operates on the following principle: Assuming a short circuit to have occurred, both of the coils are magnetized; one of them releases the clockwork, and the other forces the contact against the disc *A*. So long as the short circuit continues the magnets remain energized and maintain the parts in this condition. Should the short circuit continue during the time necessary for the discs to rotate far enough, both contact pieces will impinge against the copper facings, and so close the auxiliary line. If the trouble is relieved before contact is made, the iron pieces are drawn back into their normal position by retractile springs, thereby pulling the contact pieces away from the disc *A*, and allowing the detent to bring the mechanism to a stop after it has made one revolution, without tripping the circuit breaker. Since the solenoids operate the magnetic plugs or cores against the resistance of adjustable springs, the calibration of the solenoids is accomplished through the medium of these springs.

In order to protect all working parts from injury the mechanism of the time-limit relay is inclosed in a cylindrical glass case. It is generally located on the panel from which all outgoing circuits radiate.

Reverse-Current Relays. — The reverse-current relay usually consists of a direct-current motor of about one sixteenth or one eighth horse-power, with its field energized by a current transformer inserted in series with the line, while its armature is supplied with current from a potential transformer in parallel with the line. Mounted on the motor frame are two contacts, to which are connected the terminals of the local circuit which energizes the tripping mechanism on the oil switch in the main circuit, which is protected by the relay. The shaft of the motor carries a pair of U-shaped carbon pieces which slide against these contacts. When the current in the line is flowing normally, the motor tends to rotate away from them; but if the line current is reversed the field current of the motor is also reversed, while the direction of flow in the armature remains the same. Hence the motor rotates in the opposite direction, approximately an eighth of a revolution. This is sufficient to bring the U-shaped strips against the contacts, which closes the magnetizing circuit and trips the circuit breaker, or indicates the condition of the circuit by a visual signal.

The reverse-current relay finds use on feeders between central and sub-stations in high-tension practice; these are generally tied together by parallel lines protected by automatic circuit breakers at both ends. In the central station are two sets of bus-bars, from each of which one circuit leaves, but the lines are frequently connected to a common set of bus-bars when they reach the sub-station. Consequently, heavy overloads, or short circuits on either circuit, will affect the protective apparatus on that circuit in the same way that a short circuit on both circuits through the sub-station bus-bars would. It is for this especial

condition that a reverse-current relay is designed. The incoming leads to the sub-station are protected by reverse-current relays, while the outgoing leads of the generating station are protected by overload relays. If trouble occurs on either circuit such as to cause the operation of its protecting circuit breaker at the central station end, power will be fed back to the trouble over this line from the sub-station; this reverse flow of power affects the operation of the reverse-current relay, thereby opening the circuit at the sub-station end also. The other line is,



CIRCUIT CONNECTIONS OF REVERSE-CURRENT RELAY

Fig. 71

of course, unaffected. The reverse-current relay also finds especial application in connection with rotary converters working in parallel with other apparatus for the purpose of preventing the inverted operation of the rotaries occasioned by cutting off the alternating-current supply.

Fig. 71 shows the circuit connections of the reverse-current relay.

A reverse-current time-element relay is a protective appliance which combines the functions of all three pieces of apparatus just described, and operates to break the cir-

cuit when a reverse current of definite strength continues to flow for a predetermined length of time. The circuit breaker is actuated by differentially wound solenoids, the winding of one being taken from a potential transformer and that of the other from a series transformer. When the circuit is working under normal conditions the force exerted by the solenoid windings is negligible, each winding practically neutralizing the other. Should the current attain the value for which the mechanism has been set, the clockwork is released and opens the circuit, if the trouble continues for a definite period of time. A reversal of the current with respect to its normal flow also releases the clockwork, but regardless of the current strength because the influence of the two solenoids is now cumulative instead of differential.

Circuit Breakers. — Circuit breakers designed for use on high-tension lines are of materially different construction from their direct-current progenitors. In direct-current practice a circuit breaker is generally used in conjunction with the main switch; in alternating-current practice it becomes the main switch itself, and may be either operated by hand or tripped automatically by electromagnetic means. A type of electro-mechanical circuit breaker in which the breaking takes place in oil is shown in Fig. 72. It is of the three-pole, double-break form, and is actuated by electromagnets. Like the oil switches previously described, each element of the switch portion is contained in a separate brick cell filled with oil. Each pole or element has two stationary contacts, one of which is connected to the incoming and one to the outgoing leads of the same phase. All live parts are mounted on porcelain insulators attached to a frame made of cast iron, which also carries the oil

tanks. Across the top of the masonry structure is placed a soapstone slab in which strain insulators ,are fitted to support the cast-iron frame.

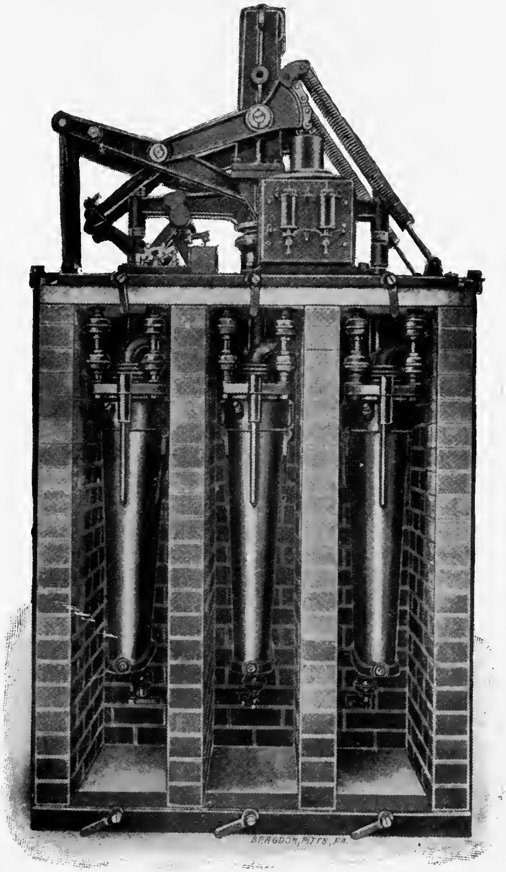


Fig. 72. A Type of Oil Circuit Breaker for High Voltages

The contact for each pole is made up of a U-shaped piece of copper attached to the end of a strong wooden rod.

When the switch is closed, one of the U-shaped copper pieces electrically connects the two contacts of each element. A common cross-bar is attached to the wooden bars at their upper ends. This cross-bar is manipulated by a system of levers to work in a vertical plane. The cross-bar is lifted by the force of the magnet which incloses it, aided at the commencement of the motion by a pair of balancing springs. The breaker is fitted with a toggle joint (which can be seen at the left of the illustration) which automatically locks the levers when the breaker is closed. The toggle joint is released by a blow from a tripping magnet, allowing the cross-bar to drop by gravity and open the contacts, its fall being expedited by a pair of stout springs. The first break occurs at the main contact, and immediately afterward at the removable plug fastened to the rigid contact; and immediately afterward at the removable contact set in a hole on the movable contact. The object of this plug is to dissipate the effects of the possible arcing. The electromagnets are energized by current derived from any convenient low-pressure direct-current source. It is also feasible to operate the circuit breaker by hand.

The oil tanks are made of thick sheet metal, lined with insulating cement. The level of the oil in the tanks is shown by a small sight gauge. The controlling and indicating apparatus of the circuit-breaker comprise a master-switch, a telltale indicator working on the electro-mechanical principle, and an incandescent lamp. Such apparatus is carried on a convenient panel. To make the circuit breaker automatic, there is provided a polyphase overload relay, which is energized from series transformers in the main circuit. The master switch, which is of the drum type, has marked on it three positions — viz. "off," "closed," and

"open." If it is put to the "open" position it will remain so when the operator's hand is removed. If, however, it is thrown to the "closed" position, it will instantly turn to the "off" position, when the handle is released. When in the "off" position, it connects the controlling circuit in such a way that if the oil circuit breaker is opened by any of the automatic appliances the operator's lamp on the stand will be lighted and thus call attention to the condition of the circuit. The lamp, however, is not lighted if the operator should throw the switch to the "open" position. The electromechanical telltale indicator consists of an electromagnet, with its armature so pivoted that it can be attracted through an angle of 90 degrees. Each switch is fitted with an overload relay operating on the principle of a single-phase induction motor.

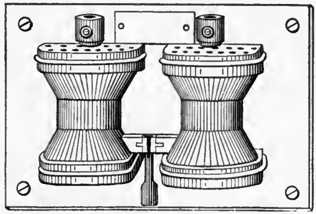


Fig. 73. A Type of Concentric Cylinder Arrester

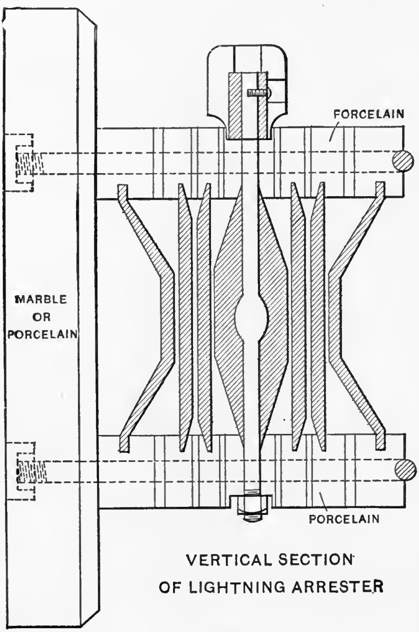


Fig. 74

Types of Lightning Arresters. — Fig. 73 shows an arrester for high-tension circuits made by the Stanley Electric Manufacturing Company. Fig. 74 shows a vertical section of the arrester.

It consists of two nests of concentric cylinders with diverging ends, which are held in position by perforated porcelain caps at the top and bottom, the caps being rigidly attached to an insulated support of either marble or porcelain. The line is grounded through the innermost cylinder. The porcelain caps are so grooved as to make all spark gaps about one sixteenth of an inch in width. The purpose of the vents in the caps is to provide a good circulation of air.

Between the line terminal and ground connection there are three spark gaps of one sixteenth inch width, thus making a total of three sixteenths of an inch air gap between either line wire and ground. With commercial frequencies, it requires a pressure of 5,000 volts to jump the gaps of the arrester, but the very high frequency of a lightning discharge reduces the arcing potential to one half this value.

The area of the discharge gap is considerably increased by the use of concentric cylinders, a large discharging area being desirable to take care of heavy discharges. For circuits of 1,000 volts, a double-pole arrester connected together by a metallic strip is used. Circuits of high potential are protected by a number of the arresters connected in series, the proper number for a given high-tension circuit being arrived at by experiment. A choke coil is connected between each arrester and the apparatus to be protected. This choke coil is made up of parts so disposed relatively to one another that the coefficient of mutual induction is very high. The coil comprises two parallel coils of insu-

lated copper strip, connected in series and wound so that the current passes through them in opposite directions. The proximity of the coils makes the coefficient of mutual induction very high ; hence with commercial currents the self-induction approaches zero.

The operation of the arrester is as follows : Lightning enters from the line to the middle cylinder and jumps the gaps in the narrow parts of the arrester; it then passes

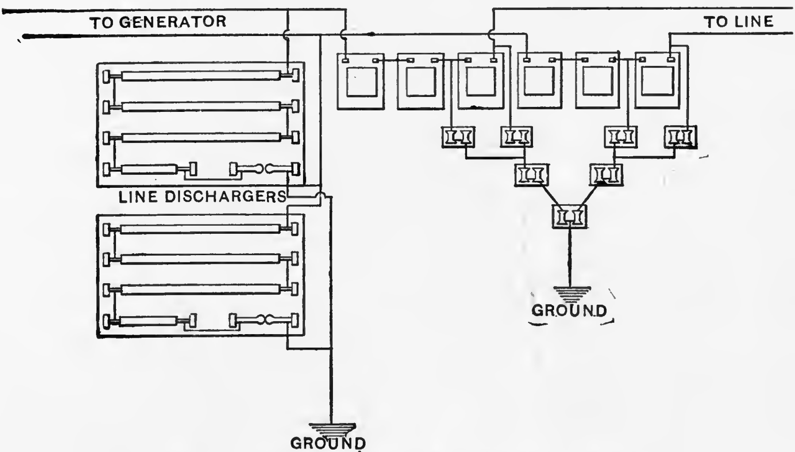


Fig. 75. Circuit Connections of Arrester shown in Fig. 73

from the outer cylinders to the ground connection. Should the generator current follow the discharge, an air current is immediately set in circulation through the vents of the porcelain caps and between the cylinders; this air current blows the arc upwards into the spaces between the horn-shaped ends of the cylinders, thereby rupturing it. With this type of arrester there is used a line discharger, the function of which is to remove static charges from the line.

The line discharger consists of a very small air gap in series with one or several tubes containing oxidized metallic particles. The tubes are about 18 inches long, and have a

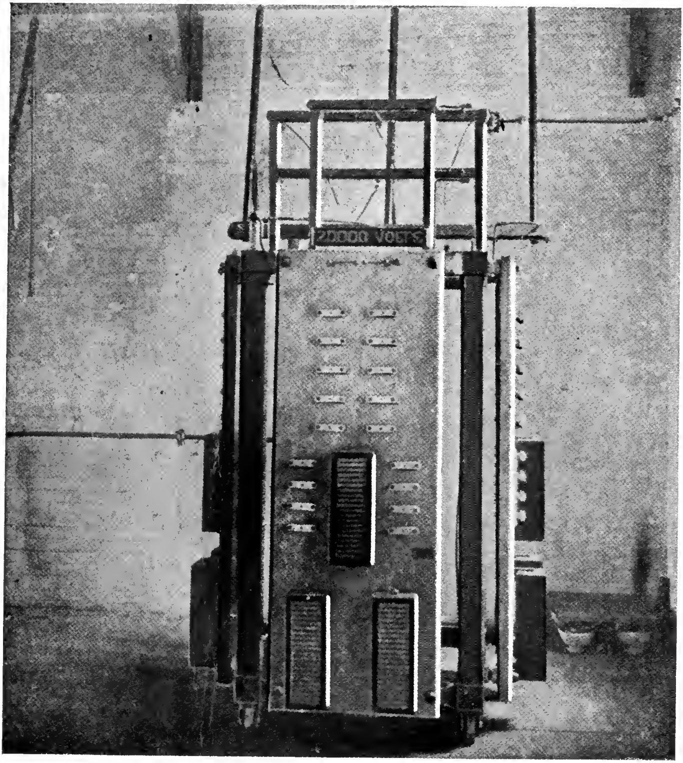


Fig. 76. Westinghouse "Low-Equivalent" Lightning Arrester

resistance of about 50 megohms — practically infinite. The small air gap is put in series with the tubes as an added precaution against grounding the line. A line discharger behaves as a selective lightning arrester. It pre-

vents dynamic currents from passing, but readily allows static discharges of low potential to pass through the tubes and over the minute air gaps and thence to ground.

The number of tubes necessary for a circuit is governed by the line pressure. Fig. 75 shows the way in which a high-tension arrester and line discharger are connected in circuit.

Fig. 76 shows a type of "low equivalent" arrester made by the Westinghouse Company and used on one of the Niagara Falls transmission lines. The circuit, after passing through a 36 inch fuse composed of No. 28 German silver wire, inclosed in a hard fiber tube of approximately seven eighths inch diameter, is led through an adjustable spark gap between small metallic balls to a bank of ten arresters, each of which has seven cylinders of non-arcing metal.

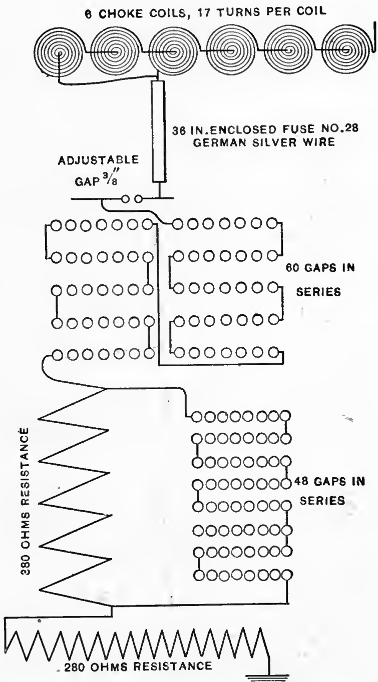


DIAGRAM OF ARRESTER CONNECTIONS

Fig. 77.

The gaps are one thirty-second of an inch in length. The diagram of the connections (Fig. 77) is self-explanatory. The discharge first takes place over the adjustable gap of three eighths inch between the balls and then over

the 60 gaps, and through the resistance to ground. The illustration (Fig. 76) shows the frame on which the three sets of arresters for the three high-tension lines are mounted. The containing panels are made of marble and are placed on three sides of the frame. The frame is placed on rollers, so that in the event a set of arresters becomes defective, the frame can be trundled away and another set mounted in its place. Line connection is made through the fuses hooking into flexible spring contacts at their upper ends. The object of the springs is to permit of changing the position of the arrester slightly should this become necessary.

Ground Detectors. — A reliable ground detector is an essential part of the protective apparatus of an alternating-current plant. As the name indicates, it is a device for indicating an earthed or grounded condition of a line. In its usual form the device consists of four fixed vanes arranged around a movable vane made of aluminum and contained in a suitable case. The movable vane is supported on jeweled bearings and is attached to a pointer.

The stationary vanes are connected in pairs, each pair by one of the line conductors through the medium of a condenser. The fixed vanes act inductively upon the movable vanes, and the stresses exerted by the two pairs is equal but opposite under normal conditions. Hence the movable vane assumes a position midway between the fixed vanes, and remains thus whether the device is charged or not, and the pointer remains at zero, denoting freedom from ground.

When a ground occurs, the primary strip of a condenser and the movable vane become electrically connected, thus causing the pair of fixed vanes which lead to that condenser

to become of like polarity with the movable vane, repelling it and causing the other fixed vane to be attracted by it. The action of the two forces in the same direction tends to make the movable vane assume a position completely within the vanes charged oppositely to it; hence the pointer deflects in a direction which indicates a ground on that side of the circuit.

Fig. 78. General Electric Ground Detector

In the best practice, the condensers for charging the fixed vanes are independent of the instrument, which obviates all danger of damage to the device by high potentials and also allows it to be installed wherever it is convenient.

Fig. 78 shows a static ground detector for high-potential circuits.

Fig. 79 shows the connections of a ground detector to a three-phase three-wire circuit.

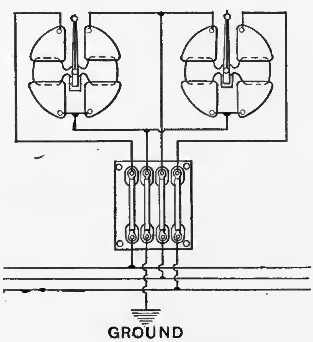


Fig. 79. Connection of Ground Detector to Three-Phase Circuit

Synchronizing Devices. — When generators are operated in parallel some device is necessary to indicate whether or not the machines are in step or synchronism. The ideal synchronizing device should indicate whether the machine being synchronized is running too fast or too slow; it should indicate the amount of difference in frequency, and should also indicate the condition of synchronism with exactness. The use of lamps to indicate synchronism is a very unsatisfactory method because

they do not perform the first function. They discharge the second function splendidly and the third function approximately. In the best modern central-station practice the only synchronizing devices employed are the Lincoln *Synchroscope* and the *Synchronism Indicator.*

The principle upon which the operation of these two synchronizing devices depends is the relative change in position assumed by a movable coil suspended in the axis of a stationary coil when the phase-relations of the currents in the two coils differ. Thus for instance beginning with a phase difference between a movable coil *A* and a fixed coil *F* of zero, a phase difference of 90 degrees will be followed by a corresponding mechanical change in the movable system of 90 degrees, and each successive change of 90 degrees in phase will be followed by a corresponding mechanical change of 90 degrees.

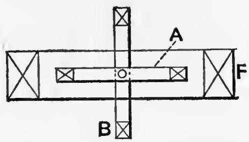


Fig. 80. Relative Positions of Coils of the Synchroscope

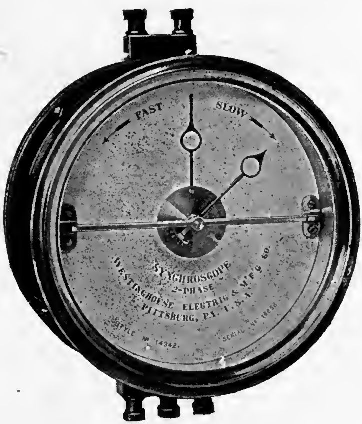


Fig. 81. The Synchroscope.

The movable system comprises a second coil *B* (Fig. 80) which is securely fastened to coil *A*, with its phase 90 degrees from that of coil *A*, and the axis of *A* passing through a diameter of *B*. Therefore, when a current passes through *B* the difference in phase relation to that in *A* will always be 90 degrees.

Under such conditions it is obvious that with a difference of phase between A and F of 90 degrees, the movable system will assume such a position as will bring B parallel to F since the force between A and F is zero, and the force between B and F is a maximum: likewise, when the phase between B and F is 90 degrees, A will be parallel to F. For intermediate phase relations it can be shown that under certain conditions the position of equilibrium assumed by the movable system will exactly represent the phase relations.

In the Lincoln Synchroscope (Fig. 81), the coil F con-

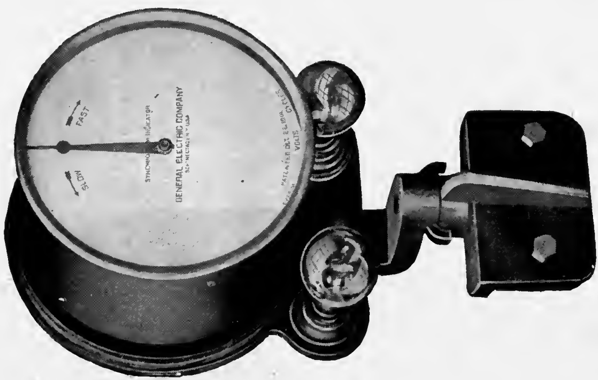


Fig. 82. The Synchronism Indicator

sists of a small laminated iron field provided with a winding whose terminals are connected with the lower binding posts. The coils A and B are windings practically 90 degrees apart on a laminated iron armature pivoted between the poles of the above field. These two windings are joined and a tap from the junction is brought out through a slip ring to one of the upper binding posts. The two remaining ends are brought out through two more slip rings, one of which is connected to the remaining top binding post,

through a non-inductive resistance, and the other to the same binding post through an inductive resistance. A light aluminum hand attached to the armature shaft marks the position assumed by the armature, the pointer moving around a dial like the hands of a clock. If the speed of the incoming machine is too fast the pointer rotates in the

CONNECTIONS WITH GROUNDED SECONDARIES ON POTENTIAL TRANSFORMERS

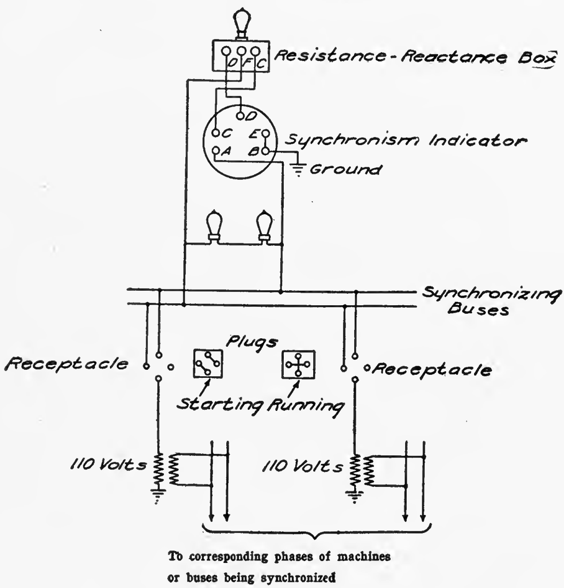


Fig. 83. Circuit Connections of Synchronism Indicator

direction marked *Fast*, and if too slow, in the opposite direction marked *Slow*.

The non-inductive resistance, which consists of an incandescent lamp, and the inductive resistance, or choke coil, are mounted within the case, thus making the instrument self-contained, no external resistance being necessary.

The current taken by this instrument is approximately one-half an ampere from each circuit.

The Synchronism Indicator (Fig. 82) is similar in construction to a small motor; the field winding being energized from the synchronizing bus-bars excited by the machine that is being operated. The armature is drum-wound and consists of two coils securely fastened at right angles to each other and connected in series.

Fig. 83 shows the connections of the Synchronism Indicator in a circuit with grounded secondaries on potential transformers. *A* and *B* are binding posts through which the field connections are made. The binding post *E* is the connection of the armature coils through a collector ring. The other two terminals are conducted to two additional collector rings, one of which is connected to the binding post *D*, thence through reactance to binding post *F*; the other terminal is connected to binding post *C* through a resistance to the same binding post *F*. The synchronizing bus-bars excited by the machine to be synchronized are then connected to the binding posts *E* and *F*. The resistance and reactance are placed behind the board, the latter being contained in a metal case, to the outside of which is secured a socket containing an incandescent lamp which serves as a resistance. Synchronism is indicated when the lamps are dark.

BIBLIOGRAPHY

Alternating Current Machines. — Sheldon and Mason. D. Van Nostrand Co., New York, 1903.

Standard Polyphase Apparatus and Systems. — Oudin. 2d Edition. Van Nostrand Co., New York, 1903.

Speed Regulation of Prime Movers and Parallel Operation of Alternators. — Steinmetz. Trans. Amer. Inst. Elect. Engrs., Vol. 18, p. 741.

The Experimental Basis for the Theory of the Regulation of Alternators. — Behrend. Trans. Amer. Inst. Elect. Engrs., Vol. 20, p. 739.

A Contribution to the Theory of the Regulation of Alternators. — Hobart and Punga. Trans. Amer. Inst. Elect. Engrs., Vol. 21, p. 183.

The Determination of Alternator Characteristics. — Herdt. Trans. Amer. Inst. Elect. Engrs., Vol. 19, p. 1092.

Compounding of Self-Excited Alternating Current Generators for Variation in Load and Power Factor. — Garfield. Trans. Amer. Inst. Elect. Engrs., Vol. 20, p. 811.

Parallel Operation of Alternators. — Lincoln. Jour. Franklin Inst., April, 1902.

Management of Alternators. — Hanchett, Central Station, August, 1903.

Mechanical Construction of Revolving Field Generators. — Rushmore. Trans. Amer. Inst. Elect. Engrs., Vol. 21, p. 145.

An Improved Method of Testing Large Alternators Under Full Load Conditions. — Behrend. Elect. World and Engineer, New York, Oct. 31, 1903, p. 715.

The Use of Group Switches in Large Power Plants. — Stillwell. Trans. Amer. Inst. Elect. Engrs., Vol. 21, p. 9.

Oil-Switches for High Pressures. — Hewlett. Trans. Amer. Inst. Elect. Engrs., Vol. 21, p. 11.

The Control of High-Potential Systems. — Rice. Trans. Amer. Inst. Elect. Engrs., Vol. 18, p. 407.

Synchronism and Frequency Indicators. — Lincoln. Trans. Amer. Inst. Elect. Engrs., Vol. 18, p. 255.

Notes on Synchronizing. — Roman. Elect. World and Engineer, New York, June 14, 1902, p. 1044.

CHAPTER V

LAWS GOVERNING ELECTRICAL TRANSMISSION OF ENERGY

Power in an Alternating-Current Circuit — Power Factor. — In a direct-current circuit the power in the circuit equals the product of the E.M.F. in volts and current strength in amperes.

In an alternating-current circuit the instantaneous power equals the product of the instantaneous values of current strength and voltage.

When current and voltage are not in phase, which is the usual condition in alternating-current circuits, there are moments when the pressure has a positive sign and the current a negative sign, and *vice versa*. The instantaneous power at such moments is of negative value, or power is being sent back into the generator by the diminishing magnetic field which had previously been set up by the current. Hence the circuit is receiving power from the generator and returning it in pulsations, the frequency of which is double that of the generator frequency.

Therefore the power in an alternating-current circuit is not the product of voltage and current but depends on the angle of current lag ϕ. Denoting instantaneous values by ($'$):

When the current lags by the angle ϕ

$$E' = E_m \sin \alpha$$

and for convenience

$$\alpha = 2\pi \text{ ft.}$$

Then

$$I' = I_m \sin (\alpha - \phi)$$

and since

$$E = \frac{E_m}{\sqrt{2}} \text{ and } I = \frac{I_m}{\sqrt{2}}$$

the instantaneous power

$$P' = E'I' = 2EI \sin \alpha \sin (\alpha - \phi).$$

But

$$\sin (\alpha - \phi) = \sin \alpha \cos \phi - \cos \alpha \sin \phi,$$

thus

$$P' = 2EI (\sin^2 \alpha \cos \phi - \sin \alpha \cos \alpha \sin \phi).$$

Since ϕ is a constant the average power through 180° is

$$P = \frac{2EI \cos \phi}{\pi} \int_0^\pi \sin^2 \alpha \, d\alpha - \frac{2EI \sin \phi}{\pi} \int_0^\pi \sin \alpha \cos \alpha \, d\alpha$$

$$= \frac{2EI \cos \phi}{\pi} \left[\tfrac{1}{2} \alpha - \tfrac{1}{4} \sin 2\alpha \right]_0^\pi - \frac{2EI \sin \phi}{\pi} \left[\tfrac{1}{2} \sin^2 \alpha \right]_0^\pi$$

which gives $P = EI \cos \phi =$ power or energy in an alternating-current circuit.

When the current leads the voltage by $\phi°$ the sign of the power equation given above becomes $+$, thus

$$P' = 2\, EI \sin \alpha \sin (\alpha + \phi),$$

which equals the expression

$$P = EI \cos \phi.$$

The quantity $\cos \phi$ depends upon the angle of lag or lead of the current, and is termed the power factor of the circuit.

The power factor is the ratio of the true watts to the apparent watts or volt-amperes. When the current and E.M.F. are in exact phase, there is no angle of lag, of course, and ϕ is zero; the power factor of the circuit is then unity.

Frequency. — The E.M.F. wave of an alternator goes through a series of positive values during the interval when a given coil on its armature passes from a south to a north pole of the field magnet, and through a series of negative values during the interval when the coil passes from a north to a south pole, or *vice versa*, according to the coil connections. When the E.M.F. (or current) passes from zero to maximum in one direction, falls back to zero, rises to maximum in the other direction, and returns to zero again, it has passed through a complete "cycle," or two "alternations." A cycle is usually designated by the tilde (~).

The number of cycles which an alternating current passes through in unit time — *i.e.*, one second — is termed its frequency, and is usually denoted by the letter *f*.

The term "alternations" is sometimes employed, and means the number of alternations per minute, unless stated to the contrary.

Frequencies in use for power transmission are generally low, ranging from 25 to 60 ~; the lower value being considered preferable when converters are used on the circuit. The higher the frequency of transmission the smaller becomes the weight and cost of transformers and the greater their efficiencies.

Electrical Factors of Power Transmission. — In the transmission of electrical energy over long distances, the following factors enter into the design of the system and, in the various ways peculiar to each, modify the character of the energy from that which it possessed at the transmitting end, or interfere with the regulation of the line: (1) inductance; (2) capacity or condensance; (3) resistance; (4) resonance, which results from a certain combination of inductance and capacity.

Inductance. — Around every conductor carrying a current of electricity there is set up a magnetic field of force. This field of force is assumed to commence its growth at the axis of the wire at the instant when current begins to flow, and in its inception it is assumed every line of force composing it has been cut once by the conductor.

As the current in the conductor grows, this ring-shaped field of force grows proportionally. Conversely, when the current decreases, the field of force decreases or collapses correspondingly, but the diameter of the field may reach zero value without absolute cessation of the current.

With a definite strength of current a conductor is encircled by lines of varying diameter. If the current is decreased, the lines of smaller diameter immediately collapse on the conductor, cut it, and disappear to a point on the axis of the conductor an instant before it is cut by those of larger diameter.

It is obvious that the number of lines of force, or, what is equivalent, the strength of the field of force, is greater for larger than for smaller currents.

The cutting of the conductor by these lines of force sets up an E.M.F. in the opposite direction to that of the E.M.F. causing the current flow; this is termed self-induction, and the E.M.F. of self-induction is always a counter E.M.F.

Self-induction or inductance tends to prevent the starting, stopping, or change in strength of an electric current. On starting up a current, the pressure of self-induction retards its flow and so prevents it from attaining an instantaneous maximum value. On stopping a current, the E.M.F. of self-induction retards its diminution and tends to keep up the flow in its original direction.

OF CALIFORNIA

The coefficient of self-induction is that number by which the time rate of change of current in a circuit must be multiplied in order to give the E.M.F. induced in that circuit. Its numerical value equals the number of magnetic lines of force linked with a circuit per absolute unit of current flowing in the circuit. The definition of "~~leakage~~" linka is the total number of lines inclosing each portion of the circuit.

The absolute unit of self-induction being too small for most determinations, a practical unit called the henry is used, the value of which is 10^9 times the absolute unit.

A circuit has an inductance of one henry induced in it when a uniform rate of change of current of one ampere per second produces a counter E.M.F. of one volt.

The physical effect of inductance in an alternating-current circuit is not only to oppose the current flow, but also to make the current lag behind the E.M.F., producing it, in the successive rising and falling between zero and maximum.

The inductance of a circuit may be made up of two components: self and mutual inductance. The former occurs when the circuit is entirely isolated, the latter when the circuit is influenced magnetically by an adjacent circuit.

Mutual inductance is due to lines of force which surround one conductor cutting a second conductor in the neighborhood of it and thus setting up an E.M.F. in the second conductor. Such an E.M.F. may either oppose or assist the current already flowing, according to the relative directions of the currents in the two circuits.

Inductance is represented by the letter L. **Mutual** inductance is represented by the letter M.

Inductance may be expressed in three ways, thus,

$$L = \frac{\Phi_i t}{I\,10^8}$$

where Φ_i is the instantaneous value of the flux through a coil of wire, t the number of turns of wire in the coil, and I the instantaneous value of the current in amperes; again,

$$L = \frac{dt}{dI}e$$

where e = instantaneous value of the induced E.M.F. in volts and $\left(\frac{dI}{dt}\right)$ ok $\cancel{dt/dI}$ the time rate of change of current; and once more,

$$L = \frac{2\,J}{I^2}$$

where J is the energy, in joules or watt-seconds.

Mutual Inductance of Circuits. — The conductors of an overhead circuit strung on the same pole line exercise a mutually inductive action upon each other, an alternating current in one tending to induce an alternating E.M.F. in the other, and the direction of the induced E.M.F. being opposite to that of the inducing current. Hence if two alternating currents flowing in parallel conductors have the same phase relation they tend to oppose each other; but if they differ in phase by 180°, which means that they flow in exactly opposite directions at any given instant, their action will be a mutually aiding one.

Assuming the angles of lag of the currents in two or more parallel conductors coming from the same leads of an alternating-current source of supply to be approximately equal, their phase relations will be the same, and they will exercise an opposing action upon each other. Such opposition tends to increase the voltage drop in a manner similar to self-induction.

Under practical conditions two alternating currents coming from separate generators do not continue exactly in phase except for short intervals of time, hence their mutually inductive action produces an opposing effect upon the currents at one instant, and an aiding effect at another instant, the character of the inductive effect changing with each change of phase relation.

Inductive Reactance. — Reactance is the effect of either self-induction or capacity, and is expressed in ohms. Inductive reactance is numerically equal to $2\pi f L$, f representing the frequency of the alternating current in cycles per second. The symbol is X_l. The effect of inductive reactance in a transmission circuit, or in the apparatus connected therein, is to increase the angle of lag and also the wattless component of the current. This component of the current is in quadrature with the energy current and does no useful work in a circuit.

The effect of the wattless component is to increase the total current, and thus increase the heating of the conductors.

In aerial wires of small resistance reactance becomes relatively very prominent. Hence it is important in some cases that conductors of moderate cross-section be adopted for transmission purposes.

Since inductance is proportional to the number of mag-

netic lines linked with a circuit, the farther apart the circuit conductors the greater will be the inductance, because the number of magnetic lines is greater. When the inter-axial distance between wires is very slight, the lines of force which encircle each wire are neutralized by those of the other wire; therefore the effect of inductance can be reduced by placing the wires close together.

With high-tension overhead wires, however, this remedy is entirely impracticable, owing to the possibility of short circuits between the conductors, and also the losses which would ensue from leakage and electrostatic induction between the wires. In high-tension practice the three general methods used to reduce line inductance are: subdividing the conductors or using stranded conductors of the same total cross-section as the solid conductor which would be required: or balancing the effect of inductance with artificial capacity (condensers or condensive apparatus introduced in the circuit at definite intervals).

The simplest means of decreasing mutual inductance is to increase the inter-axial distance between the conductors. The practical limitation of this method is the necessity of carrying the circuits on the same pole, so that mutual inductance can only be reduced in practice either by placing the conductors equidistant from each other, so that any one wire will be affected equally by the wires of the other circuit, or else by transposition of the conductors with respect to each other at symmetrical intervals along the line.

Fig. 84 shows the latter method diagrammatically as applied to a three-phase circuit. In this method, which is also used in high-tension practice, an equal length

or distance of one conductor neutralizes the action of an equal length of conductor of another circuit. Thus the inductive action of one circuit upon the other is nugatory.

Capacity or Condensance. — The capacity of a conductor is the property which it possesses of being able to receive a "charge" of electricity. The capacity of a conductor through which an alternating current is flowing is analogous to the electrostatic capacity of a Leyden jar or a condenser; the unit of capacity is the *farad*, but actual capacity values are so small that they are commonly expressed in *microfarads*. A condenser would possess a

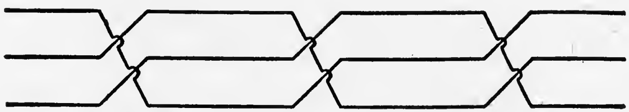


Fig. 84. Method of Transposing a Three-Phase Circuit

capacity of one farad if it were capable of taking a charge of one coulomb at a potential of one volt; or the numerical value of the capacity of a condenser in farad measure is equal to the quantity of electricity which must be delivered to it in order to increase the difference of potential between its terminals from zero to one volt.

The farad is 10^{-9} times the absolute unit. The microfarad is $\frac{1}{1000000}$ of a farad, or 10^{-15} times the absolute unit of electrostatic capacity.

The charging or discharging current of a condenser attains its maximum value when the rate of variation of effective pressure is maximum, or when the E.M.F. is of zero value at the instant of passing from negative to positive value, or *vice versa*. Hence the physical effect

of capacity is exactly opposite to that of inductance and may entirely neutralize it.

Under certain conditions the effect of capacity may cause the current to lead the E.M.F. in phase.

In long-distance transmission lines the capacity of the circuits is often of very great magnitude, and may require a large reserve in the kilowatt capacity of the generators to charge the line before working current can be gotten through.

Capacity in an alternating-current circuit produces an effect measured in ohms and termed "capacity reactance." Thus in a circuit having capacity, the flow of current increases in direct proportion with it and the frequency; hence the reactance due to capacity is inversely proportional to these quantities. Capacity reactance has the numerical value expressed by the equation

$$X_c = \frac{1}{2\,\pi f C},$$

C representing the capacity in parts of a farad. The effect of capacity in transmission lines can be overcome in two different ways: (1) by increasing the distance between the conductors and their distance from the earth; the decrease in capacity by doubling the distance between conductors may amount to as much as 15 per cent; (2) by the use of inductive apparatus in circuit. Artificial regulating impedance coils may be used to accomplish this result.

The effect of line capacity-current varies only with the voltage and frequency. As the load decreases its influence decreases, for when the load is light, it is not only entirely neutralized by inductance, but also becomes negligible on

account of the presence of a considerable current in phase with the E.M.F.

At periods when both capacity and inductive loads of a line are reduced, the line capacity-current causes the most disturbance to regulation, and on such occasions attempts to neutralize the capacity effect with inductive apparatus which is thrown off at the same time acts only to augment the disturbance.

Resistance. — An alternating-current circuit possesses resistance just as does a direct-current circuit. The resistance of an alternating-current circuit, though usually insignificant in comparison with the other characteristics, is not always negligible.

If the cross-section of a conductor through which an alternating current is flowing be divided into numerous parallel components or filaments, it is apparent that those components nearer the center suffer greater inductive effects than the components nearer the interior. Hence the streams of current near the surface meet with less opposition and attain their maximum value sooner than those in the central portions of the conductor. In case the conductor is of large area and is carrying large currents of high frequency, a condition may be attained in which the central section of a conductor may not only have no current flowing through it, but under certain circumstances the flow of current may be in the *opposite direction.*

The reduction of the effective cross-section of a conductor due to this phenomenon causes an increase of effective resistance, so that a current of slightly smaller value will flow than would be the case if only the true resistance and inductance of the conductor be considered.

This apparent increase in resistance is termed the "skin-effect." For all practical purposes it is the same as true resistance, and is expressed in ohms. In most practical cases it is negligible.

Impedance. — The resistance and reactance of an alternating-current circuit combined constitute its impedance. Impedance is the total opposition to the flow of current in a conductor and is expressed in ohms, so that with a definite impressed E.M.F. the impedance fixes the maximum current that can flow.

The numerical value of impedance is expressed by the equation,

$$Z = \sqrt{R^2 + \left[2\pi f L - \frac{1}{2\pi f C}\right]^2} = \sqrt{R^2 + (X_l - X_c)^2}$$

Resultant Impedance of Several Impedances in Series. — When a circuit includes two or more pieces of apparatus in series, each of which may or may not have resistance, inductance, and capacity, the current which flows under any impressed E.M.F. has the same phase throughout. The E.M.F.'s at the terminals of the different pieces of apparatus may be of different phases, depending upon the inductance and capacity of each, and the magnitude of each E.M.F. will depend on the impedance of the device. The determination of the E.M.F. necessary to force a definite current through a series circuit of the kind mentioned is analytically expressed by the equation,

$$E = I\sqrt{(R_1 + R_2 + R_3 + \ldots)^2 + [(X_{l_1} + X_{l_2} + X_{l_3} + \ldots) - (X_{c_1} + X_{c_2} + X_{c_3} + \ldots)]^2}$$

and since $E = IZ$, the total impedance of the several impedances in series is,

$$Z = \sqrt{(R_1 + R_2 + R_3 \ldots)^2 + [(X_{l_1} + X_{l_2} + X_{l_3} \ldots) - (X_{c_1} + X_{c_2} + X_{c_3} \ldots)]^2}$$

from which it is obvious that the total impedance is not the arithmetical sum of the individual impedances.

When a circuit has impedances in series and in parallel, or a series-parallel combination, the equivalent impedance is determined by calculating the joint impedances of each parallel group and combining them in series.

Admittance, Susceptance, and Conductance. — The admittance of a circuit is the reciprocal of the impedance, in formula shape,

$$Y = \frac{1}{Z}.$$

The equivalent admittance of several admittances in parallel is equal to

$$\sqrt{(\Sigma \text{ Inductances})^2 + (\Sigma \text{ Susceptances})^2}.$$

The susceptance of a circuit is the quantity by which E must be multiplied in order to give the component of I perpendicular to E.

Its numerical value equals

$$b = \frac{\sin \phi}{Z}$$

in which ϕ is the "angle of lag," $\sin \phi$ is the "inductance factor" of the circuit.

The susceptance may also be numerically expressed by

$$b = \frac{X^2}{R^2 + X^2},$$

X being the equivalent reactance, or the difference between the inductive and capacity reactances.

The conductance of a circuit is a quantity by which E

must be multiplied in order to give the power component of the current, or the component in phase with the impressed E.M.F. The symbol is G, and the numerical value is given by the equations

$$G = \frac{\cos \phi}{Z}$$

and

$$G = \frac{R^2}{R^2 + X^2}.$$

From the latter expression it is evident that conductance is not the reciprocal of resistance, although the two properties are opposite in character.

Resonance. — Resonance in an alternating-current circuit is that condition which enables a definite E.M.F. to produce maximum current flow at a critical frequency. Resonance takes place when the total inductive reactance equals the total capacity reactance; or, stated differently, when

$$LC = \frac{1}{(2 \pi f)^2},$$

then the two reactances entirely neutralize each other; the electrostatic energy in the condensive part being given back to the line when the electromagnetic energy of inductance is being stored in the line. When this occurs the circuit is said to be "tuned" for the definite periodicity shown by the equation

$$\frac{1}{2 \pi \sqrt{LC}} = f.$$

Hence at that particular periodicity the impedance equals the resistance, and a given E.M.F. will send through the circuit the maximum current possible.

Injury to the circuit from electrical resonance may occur when the inductance and capacity are in parallel, or are balanced, thus causing currents of enormous values to flow between the two, because each is always prepared to receive the energy discharged by the other, with the result that a see-sawing or surging action is set up between the two, and this constantly increases, due to the receipt of energy from the line. This surging or resonance effect is liable to overload the conductors between the capacity and inductance, and may sometimes destroy them by the heating produced.

If the inductance and capacity be in series, the effect of resonance may raise the potential to such a value as to break down the insulation of the generator or of apparatus along the line.

In most long-distance lines the inductances and capacities are connected in parallel, and a resonant or distortionless condition seldom occurs.

Mr. Paul M. Lincoln has expressed the opinion (Trans. A. I. E. E., Vol. 20) that "Considerations of voltage regulation at the receiving end of a line limits the voltage drop due to resistance in that line to about 15 per cent as a maximum, and the same consideration should keep the inductance volts within a maximum of 20 per cent. With a power factor of 85 per cent this means a line regulation of 24 per cent." He also states that "since the charging current depends directly upon the frequency and the pressure, the apparent energy at 60 cycles, which is represented in charging a two-hundred-mile three-phase line, is almost equal to the maximum capacity of that line limited by the 20 per cent inductance volts consideration. At 25 cycles the effect of charging current is not appreciable."

ELECTRICAL CONSTANTS OF CERTAIN TRANSMISSION LINES.

STANDARD ELECTRIC CO. OF CALIFORNIA.

Data: Length of line approximately ....150 miles
Aluminum conductors of ....75 in diameter
Area of conductors.............................471,034 C.M.
Maximum resistance per mile at 70° ....0.205 ohms
Frequency ....60~
Voltage of transmission 60,000
Distance between centres of conductors...................42′

Inductance of 150 mile line, or 300 mile transmission ....0.48 henry

Inductive reactance per mile of conductor, or ½ mile of transmission at 60~... .634 ohms

(If 30~ were used the inductive reactance would be nearly halved, or ....0.3775 ohms)

Impedance factor of line (impedance ÷ resistance) at 60~ .....3.25 ohms

(If 30~ were used the impedance factor would be ....1.84 ohms)

Resistance of 300 miles of conductor (2 wires of 150 mile transmission) .... 61.5 ohms

Inductive reactance of 300 miles of line at 60~ (2 wires of 150 mile transmission).................................190.2 ohms

(If 30~ were used the inductance reactance of the line would be ....95.1 ohms)

Impedance of 300 miles of wire at 60~ ....200 ohms

(If 30~ were used the impedance would be................113.2 ohms)

Capacity of the 150 mile transmission or 300 miles wire (considered as two parallel cylinders) ....1.43 m.f.

Capacity per mile of transmission line ....0.0095 m.f.

Capacity reactance between 2 wires, per mile of transmission at 60~ ....279,000 ohms

(If 30~ were used, the capacity reactance between 2 wires per mile of transmission would be ....558,000 ohms)

Capacity reactance between two wires of 150 mile transmission at 60~ .... 1,855 ohms

(If 30~ were used the capacity reactance between two wires of 150 mile transmission would be ....3,720 ohms)

Capacity or charging current between two wires of 150 mile transmission at 60~ and 60,000 volts ....32.25 amperes

If 30~ were used, the charging current (at the same voltage) between two wires of 150 mile transmission would be ....16,125 amperes

Apparent power required to charge the line at 60$\sim$ and 60,000 volts ....3,348 kilowatts
Real energy to charge line at 60$\sim$ and 60,000 volts ....32 kilowatts
Apparent energy to charge line if 30$\sim$ cycles and 60,000 volts were used ....1,674 kilowatts
Real energy to charge line at 3$\sim$ and 60,000 volts ....16 kilowatts
10,000 kw. at 60,000 volts and unity power factor requires 96.3 amperes per wire.
The loss in 150 mile transmission is....................855.5 kilowatts
Per cent loss in transmission 8.55
Volts loss, per pair of wires in 150 mile transmission at 60$\sim$ ..19,260 volts
Per cent volts loss, per pair of wires in 150 mile transmission at 60$\sim$ ....32.1 per cent
Volts loss, per pair of wires, in 150 mile transmission at 30$\sim$ ..10,901 volts
Per cent volts loss, per pair of wires, in 150 mile transmission at 30$\sim$ 18.2

The capacity effect on a 150 mile transmission line was demonstrated by considering a single-phase transmission of 3,000 kilowatts at the distributing end, the pressure 50,000 volts being kept constant at the sub-station.

The fairly correct supposition was used by considering the line as shunted at the generator and at the sub-station by two condensers each of one sixth the capacity of the line, and in the middle by a condenser of two thirds the line capacity.

With the line open at the sub-station, the generator pressure is only 47,676 volts, the line capacity causing the rise at the sub-station to 50,000 volts.

With 3,000 kilowatts at unity power factor at the receiving end, the current required is 60 amperes at 50,000 volts. The 32.25 amperes charging current when combined at right angles with the 60 amperes power current, requires 69.2 amperes at the generator, the resulting generator pressure being 58,800 volts. With 3,000 kilowatts at a power factor of 80 per cent at the receiving end, the cur-

rent required is 75 amperes at 50,000 volts, or 60 amperes power current and 45 amperes inductive current. The 32.25 amperes of charging current, when combined with the 60 amperes power current and 45 amperes inductive current, requires but 62.1 amperes at the generator, the resulting generator pressure being 60,000 volts.[1]

The following quantities are a few of the constants of the Bay Counties Power Company's line ·

Capacity of 150 mile circuit = 3 microfarads. Under a working potential of 40,000 volts there are :
$\frac{1}{2} \times (3 \times 10^{-6})(40,000 \times \sqrt{2})^2 = 4,800$ watt-seconds = 4,800 joules, or 3,500 foot-pounds of energy in electrostatic capacity stored in the circuit when it is fully charged.

Charging current at 40,000 volts and 60～ = 45 amperes.

The rate of supply of energy to the circuit by the generators and absorption from the circuit by the generators is

$$45 \times 40,000 \times 2 \cdot \frac{I}{T} = 1,150,000 \text{ watts} = 1,150,000$$

joules per second = 843,000 foot-pounds per second.

The generator gives out current continuously to the line for one fourth cycle. Hence the received or delivered energy during a half alternation is equivalent to the energy stored in line capacity, 3,500 foot-pounds as above.

To charge the line as a condenser requires the capacity of a 2,000 kilowatt generator.

[1] The above data are taken from Professor C. L. Cory's paper on Transmission System Regulation, read before the Pacific Coast Transmission Association, June, 1900.

BIBLIOGRAPHY

The Theory and Calculation of Alternating Current Phenomena. — Steinmetz. McGraw Publishing Company. New York. 1902.

Alternating Currents. — Franklin & Williamson. Second Edition. Macmillan Co. New York. 1901.

Alternating-Current Machines. — Sheldon & Mason. Third Edition. D. Van Nostrand Co. New York. 1903.

Choice of Frequency for Very Long Lines. — Lincoln. Transactions American Institute Electrical Engineers, Vol. 20, p. 1231.

Alternating Currents. — Hay. D. Van Nostrand Company. New York. 1906.

CHAPTER VI

THE TRANSMISSION LINE

Kinds of Conductors. — In electrical transmission plants the line represents a greater financial expenditure than any other part of the electric property. Upon its proper design and installation depend not only the economical and efficient transmission of the developed power, but also the satisfactory operation and regulation of all the apparatus in circuit; which also means the satisfactory working of the line under different conditions of load.

While refinements of design and construction are largely governed by the conditions to be met in each particular case, it is never advisable in the development of electric transmission properties to perfect the generating equipment at the expense of the transmission equipment. The bad regulation and the energy losses which ensue from faulty line construction greatly overbalance the efficiency which is gained by undue attention to the generating end of the problem

The design and construction of transmission lines are governed by several factors: (1) the amount of energy to be transmitted; (2) the working potential to be employed; (3) the length of the line; (4) the climatic conditions of the country which it traverses; and (5) the permissible losses in line drop and leakage.

The choice of conductors is confined to two metals, namely, copper and aluminum. Copper, by reason of its high conductivity, mechanical strength, ductility, and free-

dom from corrosion is more extensively employed in high-tension practice at the present time than aluminum. It is, however, being largely displaced by aluminum, on account of the superior advantages which the latter metal offers in lightness, and the consequent reduction in the weight to be carried by insulators, pins, and cross-arms.

In tensile strength, hard-drawn copper ranges from 60,000 to 70,000 pounds per square inch, while soft-drawn copper has a tensile strength of from 25,000 to 35,000 pounds per square inch. The specific resistance of hard-drawn copper, on the other hand, is from 2 to 4 per cent greater than that of the soft-drawn metal. Hard-drawn copper is also very brittle and inflexible and hence in large sizes is very difficult to handle.

The tensile strength of aluminum ranges from 20,000 to 33,000 pounds per square inch, and its specific conductivity is only 63% of that of copper of the same purity (commercial quality). Hence in wires of equal sizes and lengths aluminum must have a sectional area 1.66 times that of copper to have an equal electrical resistance and transmit a given amount of energy with equal loss. Or, since the cross-sectional areas of round wires vary as the squares of their diameters, the diameter of an aluminum wire must be 1.28 times greater than that of a copper wire of the same length to possess equal conductivity.

On the other hand, the specific gravity of copper is 8.89, while that of aluminum is but 2.7, so that a given wire of copper weighs 3.3 times as much as an aluminum wire of equal volume. Hence a copper conductor of the same length and resistance as an aluminum one is approximately twice as heavy. It is quite evident that reduction by one half of the weight on poles, insulators, cross-arms, etc.,

becomes of very great advantage in long lines, and especially when the transmission line is projected over rough sections of country.

It is also found that the vibration of transmission lines in heavy winds, which tends to make cross-arms, pins, and the fastenings of conductors work loose, is somewhat less with aluminum than with copper conductors, as ordinarily strung, on account of the smaller weight of aluminum, and the greater sag between poles which are given aluminum lines.

Since a pound of aluminum made into a conductor of any length has a sectional area 3.33 times greater than an equal weight and length of copper, and for equal resistance has one half its weight, it is obvious that when aluminum can be bought at a lower price per pound than twice the cost of copper, the former metal is the cheaper for transmission purposes.

As compared with copper, the electrostatic capacity of aluminum is from 5 to 8 per cent greater, depending upon the amount of energy transmitted and the length of the line. (For equivalent conductors, capacity is a logarithmic function of diameter divided by distance apart.) Aluminum, however, possesses several disadvantages which make it advisable to observe considerable precaution in the use of it in regions where adverse climatic conditions prevail. Owing to its larger cross-sectional area, as compared with copper, it offers a larger resisting surface to wind storms, which if not actually destructive may permanently elongate it, and so give rise to dangerous sags in the line. Its greater diameter also affords a larger surface for the accumulation of ice, which on account of the low ductility of the metal may cause a breakdown in the line. The very high coefficient of expansion of aluminum with change of

temperature is also a very objectionable feature in regions subject to erratic or wide fluctuations in temperature, and renders line-stringing exceedingly difficult.

Aluminum is also greatly subject to electrolytic corrosion, and is readily attacked by the fumes from chemical works, especially when they contain sodium. It is a highly electro-positive metal, and when exposed to the atmosphere in contact with any other metal, an insidious electrolytic action ensues in which the electrolyte is the moisture of the air contaminated with chemical impurities. This property of the metal has rendered the proper construction of joints in an aluminum transmission line a matter of extraordinary difficulty.

Most of the breakdowns and consequent dissatisfaction with aluminum as a conductor are due to a disregard of the electrical character of the metal. If it becomes absolutely necessary to solder the joints of an aluminum line, or to use a joint composed of aluminum and another metal, the joint must be waterproofed so thoroughly that not a particle of moisture can come in contact with the metals composing it. The usual joint employed and one which obviates all difficulties from corrosion, consists of an oval aluminum tube (similar to the McIntire joint), about ten inches in length, which is twisted some three or more times around itself after the ends of the conductors to be united have been introduced.

An objectionable feature of aluminum when used in small sizes is the low fusing point of the metal. It melts at 1157° F., while copper melts at 1929° F., and wrought iron at 2800° F. Hence if an iron or copper wire falls across an aluminum line, the latter might readily be melted in two by the current flow through the cross, while the

wire causing the trouble would not be affected. True, this is an easy method of eliminating the trouble, but at the serious expense of interrupting the service.

As regards energy losses, there is but little difference between the two metals, the advantage being in favor of copper. As regards cost, the advantage is greatly in favor of aluminum. In fact, one of the main reasons for its use, outside of the physical properties enumerated, is the comparative cheapness of the metal.

Aluminum is used as an aerial conductor only in the stranded or cable form, and only in the bare form. The solid wire shows considerable lack of uniformity of strength, even in the same sample, and breakdowns in lines constructed of solid metal are not infrequent.

When copper is used as the conducting medium for high pressures, it is always in the form of bare, medium hard-drawn, solid, round metal. The experience in American high-tension practice is that copper wires smaller than No. 5 B. & S. gauge should not be used on long-distance lines.

Relative Weights of Metal Required for Single-Phase Two-Phase, and Three-Phase Circuits. — In long-distance power transmission, a problem of highest importance is the determination of the system which will give the greatest efficiency of transmission with the best economy of material, and which at the same time will be thoroughly reliable in its operation. Application is made of the general law of copper-conducting circuits, that the weight of copper is inversely proportional to the square of the voltage, other things being equal.

The accompanying diagram (Fig. 85), taken from Dr. C. P. Steinmetz's classic "Alternating Current Phenomena," shows the relative weights of copper needed for

the various systems. The standard chosen for comparison is the single-phase two-wire system, for which the percentage of copper required is 100.

Considering first the single-phase three-wire system: If the voltage of the two-wire system is e, the pressure be-

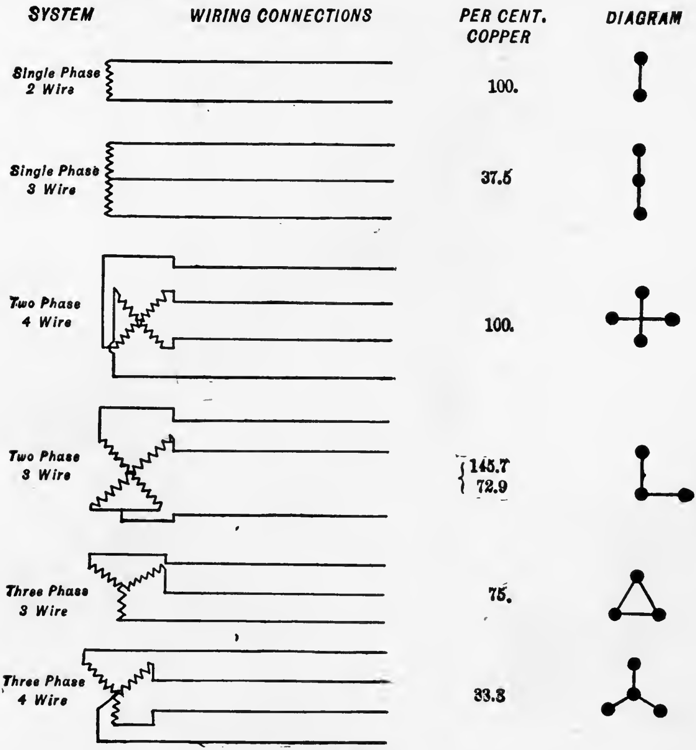


Fig. 85

tween the two outside conductors is $2e$. But since the amount of copper is inversely proportional to the square of the voltage, the weight of copper is but one quarter when the neutral conductor has no cross-section, or when the system is balanced, thus dispensing with a neutral return conductor.

When the cross-section of the neutral conductor is equal to that of an outside conductor, the maximum amount of copper required for a single-phase three-wire system is 37.5 per cent of that required by a two-wire single-phase system.

When the neutral wire has one half the cross-section of each outside conductor, the maximum amount of copper required is 31.25% of that of the standard system. When the neutral has one third the cross-section of the outside wire, the amount of copper needed is 29.15 per cent of the standard system.

For a two-phase four-wire system, which is the equivalent of two single-phase systems, the amount of copper required is the same as that needed by two single-phase two-wire lines.

When a two-phase three-wire system is used the determination of the necessary copper is more complicated. When a conductor of full cross-section is substituted for two of the leads of the four-wire system, the pressure between the two outside conductors is increased to $\sqrt{2}\,e = 1.41\,e$, e being the voltage between the conductors of either phase. Hence the amount of copper necessary will differ according to whether the basis of comparison is the maximum permissible potential for a given distribution or the minimum potential for low-pressure work.

When insulation stresses or other causes limit the highest permissible pressure to e, thus reducing the voltage between the other leads of a two-phase three-wire system to $\frac{e}{\sqrt{2}}$, the amount of copper needed is 145.7 of that of the standard system. When limitations of working potential do not hold, the basis of comparison is the effective pressure of either phase, or a minimum pressure consider-

ation. The economy in copper over the single-phase system is, under such conditions, 27 per cent, or 72.9 of the copper required by the single-phase standard system.

For a three-phase three-wire system the weight of copper necessary for any definite set of conditions is 75 per cent of the copper required by the standard system.

With three-phase systems, the comparison of relative weights of copper is easier made if the system be resolved into a number of single-phase systems corresponding with the number of phases.

A three-phase system is made up of three single wires with no return conductor, since the maximum current to and from the middle is zero. The voltage of the line is e, and the pressure between any wire and the neutral point of the system is $\frac{e}{\sqrt{3}}$.

For a three-phase four-wire system with a neutral of full cross-section, the weight of copper necessary is $33\frac{1}{3}$ per cent of the standard single-phase system. If the cross-section of the neutral wire be made one half that of the main wires, the weight of copper necessary is 29.15 per cent of the standard system. A system of this kind is only used for distribution from transformer secondaries; hence it is compared with other systems only on the basis of equality between phases of minimum voltage.

The choice between transmission systems for long-distance lines is practically confined to the two-phase three-wire and the three-phase three-wire systems. The question as to which is preferable is still a mooted one. For all-round service the three-phase three-wire system offers the advantages of simplicity in line construction, greater economy in copper and higher efficiency of trans-

mission. But the two-phase three-wire system gives on the whole a better line regulation and is much more reliable for loads made up entirely of motors.

The majority of long-distance power transmission companies in the United States employ the three-phase three-wire system for transmitting the energy, and the two-phase four-wire system from step-down transformer secondaries, for distribution, with mixed loads.

The accompanying tables from Steinmetz's "Alternating Current Phenomena" show the copper efficiencies of the various systems on the basis of maximum and minimum differences of pressure.

Amount of copper required for transmission at a given loss, based on minimum potential.

System.	No. of Wires	Per cent Copper
Single-phase	2	100.
Single-phase	3	37.5
Two-phase, common return	3	72.9
Two-phase	4	100.
Three-phase	3	75.
Three-phase, neutral full section	4	33.3
Three-phase, neutral one-half section	4	29.17

Amount of copper required for transmission at a given loss, based on maximum difference of potential.

System.	No. of Wires	Per cent Copper
Single-phase	2	100.
Two-phase, with common return	3	145.7
Two-phase	4	100.
Three-phase	3	75.
Direct Current	2	50.

Transmission Line Poles. — Poles used for supporting long-distance transmission lines are of cedar, chestnut, pine, redwood, fir, or spruce. The use of a particular wood for a pole line depends upon the expenditure allowed for line construction, the factor of safety desired, and the prevalence of a particular and readily obtained wood in the section of country through which the line passes.

Cedar poles are in extensive use, owing to their great durability, but are seldom used in lengths greater than 50 to 55 feet, since cedar poles of greater height and having suitable dimensions are difficult to obtain, and if obtainable their cost is prohibitive. The brittleness of the wood also precludes its use on lines which must be strung at considerable distances above the ground.

On account of its cheapness and abundance pine is more widely used for line support than other wood. Although not near so durable nor stout as some of the other woods, such as cedar or redwood, its cheapness and the ease of obtaining it compensate in many cases for these disadvantages.

Along many of the Western transmission lines which traverse mountainous regions the most abundant woods are several varieties of fir and spruce, which are extensively used in pole lines on account of their straightness and toughness and the readiness with which they can be obtained in the proper sizes.

In California transmission circuits, considerable redwood is used, which is always of rectangular section, because of the great size of the redwood tree and the necessity of cutting it up into sections for poles.

It is advisable to treat poles of soft woods such as spruce and pine with some kind of preservative before they are

set in the ground, but owing to the added expense this treatment is seldom given to poles for high-tension lines. Some Western transmission companies, however, apply hot tar or carbolineum to the butts of the poles or bore into the centers and give them fillings of the latter compound.

While the sizes of poles used in long-distance transmission lines vary considerably with the special conditions which must be met, it may be said in general that the length is never under 30 feet and the diameter at the top is never less than 7 inches. In the mountainous sections of the West, the length of pole used is seldom greater than 30 or 35 feet, with a top diameter of 8 inches; but on level stretches the poles are five or more feet higher as a precaution against mischievous attempts to throw obstructions over the line. The average length of the poles for high-tension transmission lines is about 40 feet, with a butt diameter of 10 inches and tapering to $8\frac{1}{4}$ inches at the top. The length of the poles should be so proportioned to the contour of the region that the line may be laid out without any abrupt changes in its level. In crossing other pole lines, such as telegraph and telephone lines, it is customary to use poles of sufficient height to carry the high-tension line at a safe distance above the other line, in order to reduce the liability to crosses.

Poles are generally set in the ground to the following depths:

Height of Pole	Depth of Setting
35 to 45 feet	5 to 6 feet
50 " 55 "	$6\frac{1}{2}$ " $7\frac{1}{2}$ "
60 " 80 "	$7\frac{1}{2}$ " $8\frac{1}{2}$ "

The length of life of poles varies quite markedly, being dependent upon the character of the wood, the kind of soil

in which it is set, and the climatic conditions of the region. The life of a cedar pole varies from fifteen to twenty years and not infrequently they last thirty years. The average length of life of a chestnut pole is twelve years, while that of a pine pole is from six to ten years. Redwood and fir poles last almost as long as cedar.

Construction of Pole Lines. — The construction of the pole line must be carried out with scientific accuracy in order to obtain the highest efficiency of service and freedom from line troubles. Hence in most pole-line construction the line should not only be staked out by a surveyor, but the poles should be set with plumb bobs, and the construction chief should use a thermometer and a set of curves to determine the correct sag to allow the wires at different points along the route. When the section of country through which the line passes is smooth and level, and where the soil is of a character which will hold the pole rigidly in position, no especial difficulties are encountered in the erection of poles. Under such conditions the points for the holes are carefully located and the excavations made to the proper depth. The poles having been distributed at the holes, each pole is set in position by from four to ten men, depending on its dimensions; the earth is firmly tamped around its butt and the task is finished.

In case the line must traverse marshy or "made" ground, it becomes essential to put a concrete mixture around the pole, composed in some instances of one part of cement, three parts of sand, and five parts of broken stone.

Where the pole must be set in rock, the butt should be hewn to fit a suitable iron shoe, which is rigidly bolted to the rock. To prevent corrosion of this shoe, it should be painted on the inside with white lead before the pole is in-

serted. The outside of the shoe should be left smooth, and hydraulic cement spread over the top surface of the rock on which the shoe is set.

It is the general rule in Western practice to place two poles together whenever an angle is made in the line, so that the strain will be equally divided between the two.

The absence of guy wires in pole-line construction is quite common on the Pacific coast; wooden struts are in more general use. Those usually employed average 6 inches by 6 inches, and are attached to a "dead man" buried about 5 or 6 feet in the ground. In cases where it becomes imperative to use a guy, the strut is sometimes used as an anchor, or else a piece of timber about 6 inches by 6 inches by 20 feet long is inserted in the guy to serve as a sort of strain insulator.

Transmission lines operating at high potentials are generally run over a private right of way, varying with the conditions from 60 to 300 feet in width. Where the line goes through forests, the trees on each side of it must be cleared away to a distance sufficiently great to prevent trees felled by wind or lumbermen from falling across the line wires.

Since the majority of high-tension lines furnish power to enterprises to which an interruption of the service would entail serious loss and inconvenience, it is generally customary to install the lines in duplicate. The first practice was to install both circuits on the same pole line, but inductance and short-circuit troubles render it imperative to construct a separate and similar transmission line.

Although the use of duplicate lines insures continuous service, it is found that unless the most improved form of oil switches are used in the plant that even the brief shut-

downs occasioned by switching from the defective to the duplicate circuit causes some dissatisfaction. This is largely due to the fact that the opening of the line by ordinary types of switches is rather a slow process, and is attended with considerable hazard, as surges of a destructive character may follow.

Stresses on Pole-Lines. — Stresses on pole lines are made up of the following components: (1) Weight of conductors and the force acting downward due to conductor tension. Since the factor of safety of a pole is usually about 90 or above this first component is negligible. (2) Bending moment caused by the pull of the conductors when angles or turns are made in the line. (3) Wind stress on conductors and poles. (4) Wind stress and the weight of ice on the line.

A fairly accurate value of the bending moment may be obtained by the following formula:

$$M_b=\frac{C_a SR}{4\,D}$$

where M_b = bending moment.

C_a = area of the pole at the ground.

S = strength of pole per unit cross-section.

R = radius at the ground.

D = distance between ground and the center of pressure.

The bending moment caused by a turn or angle is

$$2\,T\cos\frac{\phi}{2},$$

where T is the tension and ϕ the angle between the conductors at the turn.

To find approximately the wind pressure on a line, the following formula may be used:

$$P=0.05\ Wd_a l_f+S_c$$

in which

W = wind pressure per square foot.

d_a = average diameter of pole.

l_f = free length of pole above ground.

S_c = pressure on conductors, *per se*.

To find the stress due to wind and ice:

$$T = \frac{(100)^2 \times \text{weight of conductors per foot}}{8\,d}.$$

Cross-Arms — Methods of Attaching. — Cross-arms used in high-tension practice are made of cedar, chestnut, oak, red and yellow pine, and redwood. They are usually rounded or chamfered at the side-top to prevent the accumulation of water in the grain of the wood.

Cross-arms vary in length and cross-section with the conditions which must be met, such as the weight of the conductors, the distance apart of the conductors, the size of insulator pins and insulators, and the wind and ice stresses which they must withstand.

No special rule applies for the dimensions of cross-arms for a given transmission voltage. It may be said in general that for pressures ranging from 10,000 to 20,000 volts the length of cross-arm varies from four and a half to eight feet depending upon the distance between wires.

Fig. 86 shows the standard 10,000 volt cross-arm used by the California Edison Company, and Fig. 87 shows the dimensions of the cross-arm used on the 33,000 volt pole line of the same company from Santa Ana to Los Angeles.

Cross-arms in the latest transmission lines in the West are made of carefully selected kiln-dried Oregon pine, 6 inches by 6 inches, and of lengths depending upon the distance between wires.

It has now become quite general practice in the West to

give cross-arms one or the other of two kinds of treatment before they are attached to the poles. In the first method, after being thoroughly kiln-dried, they are placed in an

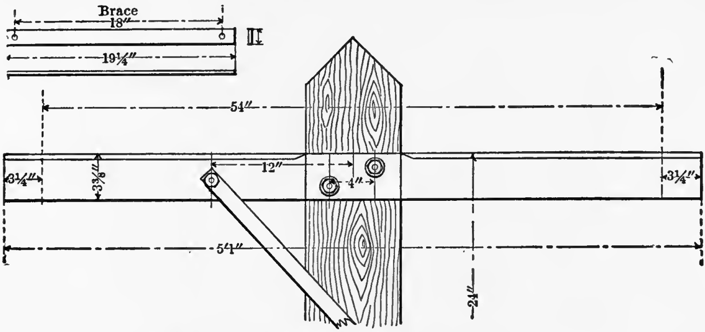


Fig. 86. Cross-Arm Used on a 10,000 Volt Line

inclosed boiler filled with asphaltum oil, which is maintained at a temperature of about 220° F. for several hours. This serves two purposes: It preserves the wood, and it

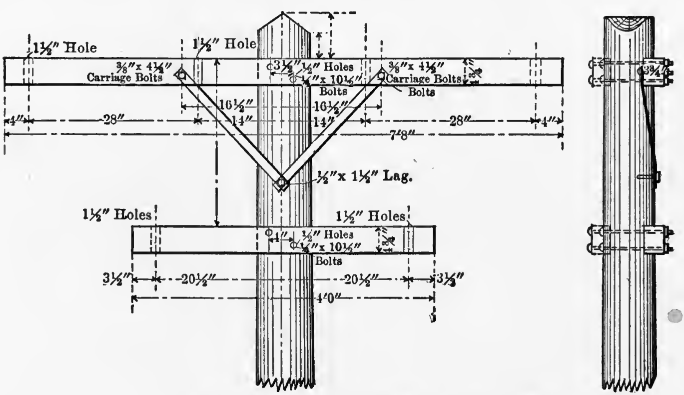


Fig. 87. Cross-Arm Used on a 33,000 Volt Line

increases the insulation of the cross-arm and pole top and tends to prevent the burning of the arm when an insulator

pin proves defective, or when a short circuit occurs on the line.

The second mode of treatment consists in boiling the cross-arm thoroughly in linseed oil.

Cross-arms are fastened to poles either by means of lag screws or by through bolts of from five eighths inch to three fourths inch diameter, fitted with cast-iron washers about 3 inches in diameter, under both head and nut. The use of through bolts is somewhat objectionable for the reason that when a cross-arm must be replaced it is frequently necessary to use a drift pin to drive out the rusted bolt.

Cross-arms for very long pole lines being necessarily very heavy and lengthy require to be stoutly braced. For this purpose single-piece angle iron is quite commonly employed. Fig. 88 shows a bracing frequently employed.

The advantage of a single-piece brace lies in the fact that if one of the line conductors should slip from its insulator down on the cross-arm, and thus be burned in two at the middle, the two ends supported by the angle-iron brace may be preserved intact without interrupting the service.

In order to overcome the effect of line strains and windage, cross-arms are sometimes braced on both sides of the pole. As a precaution against the splitting of cross-arms, when severe stresses are brought to bear against the pins, carriage bolts one half inch in diameter are sometimes mounted at a distance of 3 inches from the pin, and approximately 2 inches from the top of the cross-arm. A series of tests conducted by a California transmission company showed that cross-arms could be split without these bolts by a force of 1,200 pounds, whereas with the bolts in place the pin split at the shoulder under a force of 2,200 pounds.

On straight runs of considerable length, cross-arms are set to face each other alternately on adjacent poles, and are placed back to back on the next two poles. This method of construction obviates the danger of a cross-arm being wrenched off if a pole should break, or if a stretch of line is broken.

Cross-arms should be doubled at all long stretches and corners, and whenever the line is dead-ended. To accom-

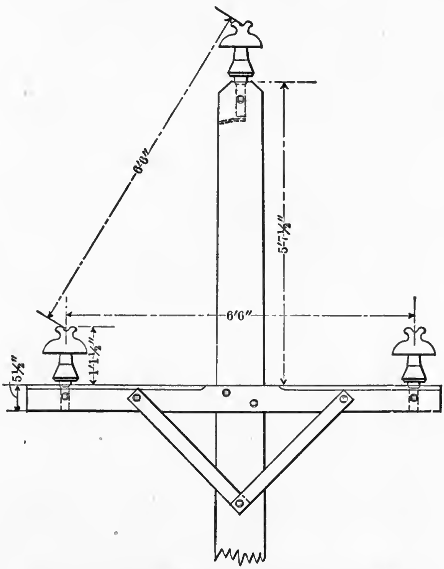


Fig. 88. Usual Method of Bracing Cross-Arms

plish this, a spacing block is used at each end of the cross-arm, and the arm is fastened at the ends by bolts through the spacing blocks.

Methods of Preserving Wood. — The principal causes of the decay of poles and cross-arms are the fermentation of the sap and the alternate wetting and drying to which they

are subjected; the latter trouble makes the wood crack and split and invites early decay on account of the settling of water in the grain of the timber.

Six methods are employed for the preservation of wood, viz.: *Creosoting, vulcanizing, burnettizing, kyanizing, carbolining, and smearing with pitch or tar.*

In creosoting poles, they are loaded on a flat car, separated by laths or strips of wood; the cars are then run into an immense cylinder fitted with air-tight iron doors; with the doors closed, live steam at a temperature of about 250° F. is turned in the cylinder until the heat causes the albumen of the sap to coagulate. The sap is then extracted by forming a vacuum in the cylinder. When this is accomplished coal tar or some variety of dead oil is forced into the cylinder under a pressure of about 125 pounds per square inch. The quantity of oil used varies with the kind of timber and ranges from 12 to 24 pounds per cubic foot.

Vulcanizing is carried out by subjecting the wood to a temperature of several hundred degrees Fahrenheit in closed chambers, under a pressure of 150 to 200 pounds per square inch. Usually heating for about a half day suffices. The heat so alters the character of the sap that no fermentation ensues.

Burnettizing is accomplished by forcing a 1 to 3 per cent solution of chloride of zinc into the pores of the wood. But since this is easily washed out in several methods, as for instance the Thilmay process, it is aimed to prevent this by the use of two different chemical solutions which react to form an insoluble salt. In the Thilmay process sulphate of zinc is first injected, followed by barium chloride. The reaction which follows results in

zinc chloride and barium sulphate, which latter compound is insoluble.

Kyanizing is carried out by immersing the wood for some time in a 3 per cent solution of bichloride of mercury.

The carbolining process is effected either by soaking the timber in carbolineum oil at 200° to 300° F., or else by injecting the hot oil into the center of the material by boring small holes into it. This method of preservation is more generally employed in Western pole-line construction than any other.

Smearing the butts of poles with tar or pitch is quite commonly resorted to, but it is harmful unless the wood is well seasoned. When applied to a wet or unseasoned pole, tar or pitch promotes decay, as it seals the pores of the wood and accelerates the fermentation of the sap.

Steel-Supporting Structures for Transmission Lines. — The peculiar troubles to which pole lines are liable, such as damage by wind storms, burning of cross-arms, necessity of constant replacing on account of decay, not excepting the need of frequent patrolling, have prompted considerable discussion relative to the advisability of using steel towers instead of poles to carry long-distance high-tension circuits. Fig. 89 shows a type of steel tower used in the seventy-five mile power transmission circuit of the Ontario Power Company, from Niagara Falls to Montreal. The proposition offers many advantages as a means of decreasing the number of breakdowns and the general maintenance of lines, although the initial cost of such construction is somewhat greater than with poles.

It has been proposed to use steel towers about ninety feet high and about 1,000 feet apart, the wires to be sus-

pended from tower to tower and about nine feet distant from each other.

As regards the advantages and disadvantages of steel

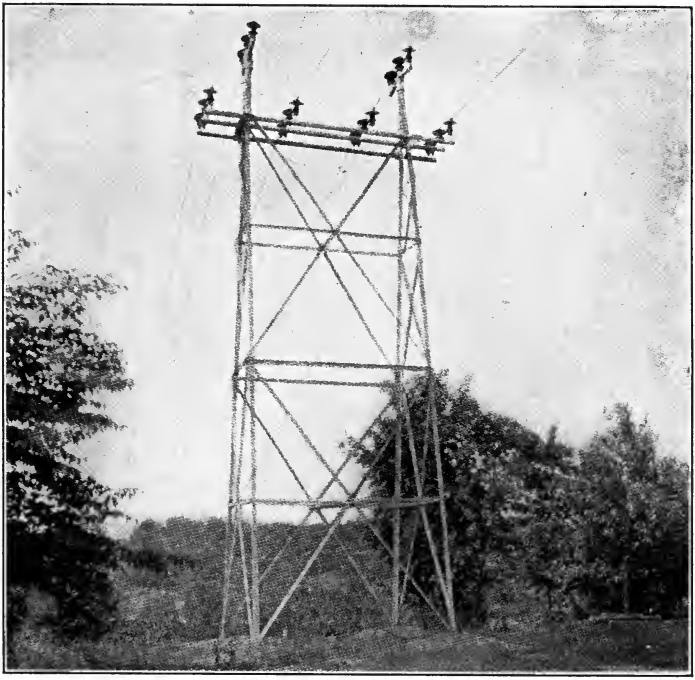


Fig. 89. Type of Steel Tower Used in Niagara Falls — Montreal Transmission

structures and poles for long-distance line construction the following comparison may be made:

At least fifty poles per mile are required, necessitating the use of 150 insulators per mile for a three-wire circuit. With steel towers, which can be spaced 500 feet apart or ten spans per mile, the number of insulators required is about thirty per mile. This large reduction in the number

of insulators makes up for the difference in cost of installation, even when poles are cheap.

Most of the trouble on high-tension lines is due to breakage or failure of insulators. From the figures cited as to the Guanajuato towers (pages 200–201) it is evident that steel supporting structures reduce such maintenance nearly 80 per cent.

Wood poles are liable to damage by lightning, prairie and incendiary fires, and in remote districts may be hacked to pieces by the natives for fuel.

Few climates allow wood poles to remain safe at the ground line more than five years. In some semi-tropical and tropical climates eighteen months measure the life of a wood pole, thereby entailing constant expense for maintenance. With steel-supporting structures this expense is obviated.

Lightning does not damage steel towers, and with proper protective devices, the use of which is impossible on pole lines, the insulators and conductors may be projected so as to reduce the lightning damage to a minimum; this damage in mountainous regions and the tropics is one of the heaviest items in the maintenance account of a pole line.

The following prices are current on steel towers (Aermotor Company):

40 ft.	towers	weighing	approximately	1,400 lbs.	$46.00
50 ft.	"	"	"	1,730 lbs.	57.00
60 ft.	"	"	"	2,000 lbs.	68.00
70 ft.	"	"	"	2,575 lbs.	84.00
80 ft.	"	"	"	2,900 lbs.	102.00
90 ft.	"	"	"	3,500 lbs.	123.00

The approximate cost per mile of constructing a high-tension circuit with a pole line and with steel towers is as follows:

53 wooden poles, 35 ft. with cross-arms and pins, at $6.00 each	$318.00
Erection, $1.20 each	63.60
3 × 53 insulators at $1.50 each	238.50
	$620.10
9 steel towers, 45 ft. with cross-arms and pins, at $60.00 each	$540.00
Assembling and erecting at $7.00 each	63.00
3 × 9 insulators at $1.50 each	40.50
	$643.50

In Mexico several long-distance lines have been projected in which the entire circuits are to be supported on steel structures. Fig. 90 shows the type of tower used on the 110 mile, 60,000 volt transmission of the Guanajuato Power and Electric Company, and built by the Aermotor Company, of Chicago, Ill. Fig. 91 shows the method of erecting the tower. The towers employed on this line are uniformly 40 feet in height, and for particular locations were provided with 20 foot extensions to permit the stringing of the conductors 60 feet above the earth. The weight of the tower is approximately 1,500 pounds.

The towers are spaced 440 feet apart, making twelve spans per mile, and carry conductors about $\frac{5}{16}$ inch in diameter, with 17 or 18 feet sag between insulators. The side strain impressed upon the insulators, should the conductor break between supports, would be about 900 pounds if no slippage occurred at the insulator.

It was found by actual test that the extra heavy pipe which extends six feet above the top of the tower (Fig. 90) and has attached to it a cast-iron insulator pin, stood the same pressure, 900 pounds, without being bent beyond its elastic limit.

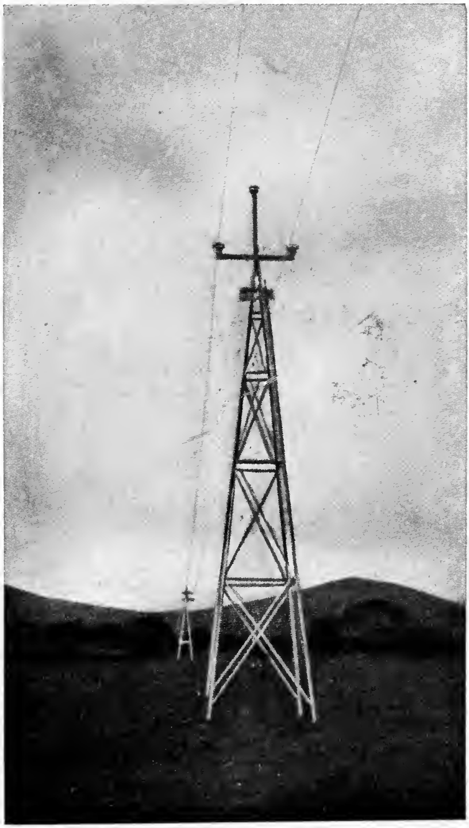


Fig. 90. Type of Steel Tower Used on a Mexican Long-Distance Line

The cross-arms, which are made of two 4 inch channel irons, weighing $5\frac{1}{2}$ pounds per foot, clamp to the pipe immediately above the apex of the tower, and are bolted to the two side insulator pins.

The maximum side strain which can be impressed upon a tower, should three wires break on one side, is 2,700 pounds. The tower itself, properly anchored, safely stood a strain of 2,500 pounds, which gives it some excess in strength over that of the conductor connections.

The tower is put together with bolts, clamps, etc., and is assembled on the site. All parts are thoroughly galvanized. A set of ladder steps to attach to one corner post of the tower is provided to enable linemen to ascend the structure, and also a small platform near the apex to form a support for linemen when putting on insulators.

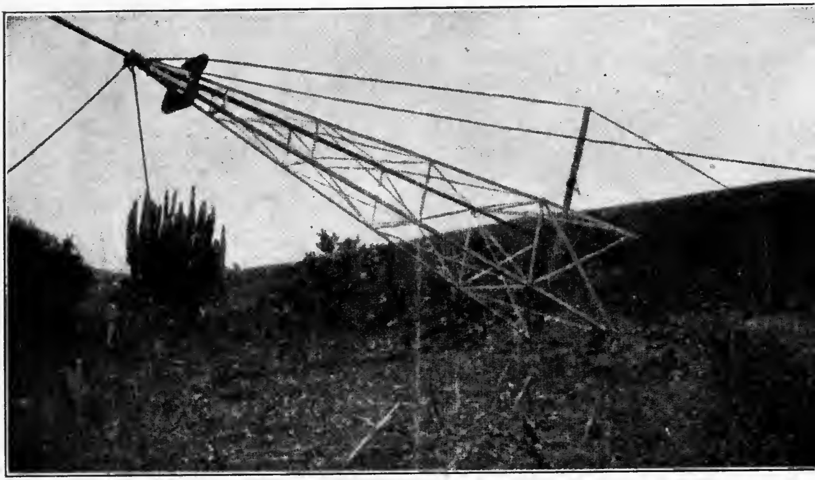


Fig. 91. Method of Erecting Steel Tower Shown in Fig. 90

The anchorage of the towers consists of steel anchor posts 6 feet in length, with a stout cross-piece on the higher towers. These anchor posts were set firmly in the ground and weighted with rough stone and rubble, thus forming a secure and solid foundation for the structure. The cost of the towers, including cross-arms and insulator pins, was $53 each.

Fig. 92 shows a twin-type steel tower designed to carry two high-tension three-phase circuits.

Kinds of Insulator Pins. — Pins for carrying high-tension insulators are either wooden or metallic. Wooden pins are more extensively employed at the present time, but are being gradually displaced by iron pins on account of the many points of advantage which the latter possess. Wooden pins are made of chestnut, oak, eucalyptus, or locust. In California redwood pins are in quite general use, but locust and eucalyptus offer the largest number of points of superiority.

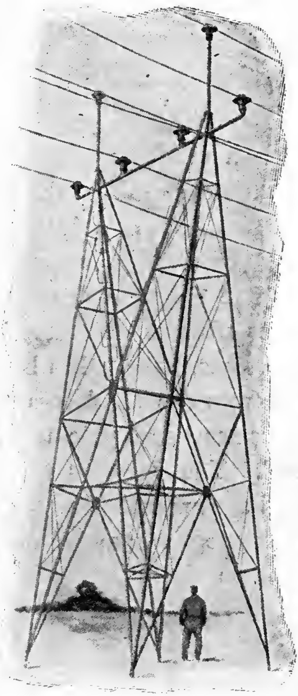


Fig. 92. Twin-Type Tower for Two Three-Phase Circuits

Locust is the toughest and most lasting of woods, but is harder to obtain and much more expensive than some other varieties of timber. Oak pins when properly proportioned and carefully treated have given excellent satisfaction, but some experience has shown that they have a tendency to decay in a few years and break off at the shoulder.

On the Pacific coast eucalyptus wood is almost entirely used for insulator pins on account of its immunity against the attacks of worms and insects. These pins are given the following treatment before they are put into use: The wood is first cut into sticks about 3 inches square, which are then immersed in boiling water for about a day.

After this preliminary treatment they are air dried for several months before being cut into the desired sizes for pins. Before being mounted on the cross-arm they are boiled for several hours in linseed oil, at a temperature of about 210° F. (In the best practice wooden pins are always boiled in paraffine or linseed oil before being put into use.)

Holes for wooden pins average $2\frac{1}{4}$ inches in diameter and 5 inches deep. In general, holes of these dimensions leave a margin of about 1 inch of solid wood in the cross-arm on each side of the hole.

One of the principal objections to wooden pins is the liability to become charred or to be burnt out entirely by leakage currents over the insulator. Burning generally takes place at the thread of the pin. In some transmission lines, trouble has been experienced by the current arcing from the insulators to the pins, and even crossing to cross-arms and pole tops, and forming, supposedly, nitric acid. The elements for the hydrogen and oxygen of the acid are present in water which settles on the wood, while the nitrogen comes from the air. The acid thus formed acts on the wood and makes it quite pulpy. Since nitric acid is also a splendid electrical conductor the tendency of the current to strike from insulator to pin is greatly increased; and hence in time the thread of the pin and other parts become charred and finally break off, or burn out entirely.

It is supposed that burning or charring of pins at the threads is due to the high resistance of the pin at this point, which results in the evolution of a high temperature by the leakage current from the insulator. At the lower part burning seldom occurs, as the accumulation of

dust and organic matter affords a fairly good path for the current.

Another serious drawback in the use of wooden pins is that a defective insulator, or a breakdown of an insulator, usually results in the complete destruction of the pin and not infrequently in the burning of the cross-arm.

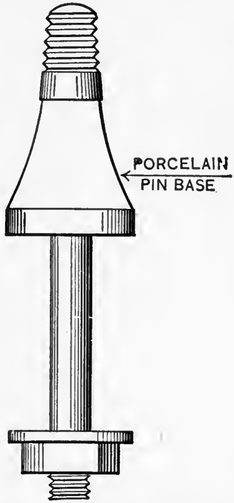


Fig. 93. Iron Insulator Pin with Porcelain Base

Metallic pins are generally made of wrought iron, and are constructed with either wooden screw threads and porcelain bases, or else with wooden tops and iron bases, or with wood tops and wood bases. The pin proper, or bolt, which holds the insulator in position varies in dimensions from one half inch by 10 inches for medium-sized insulators, up to five eighths inch by 11 inches for very high pressures and heavy insulators.

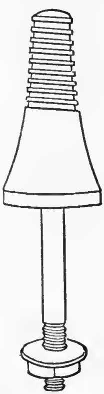


Fig. 94. Iron Pin with Wood Top

Fig. 93 shows a Locke iron pin with a porcelain base, and Fig. 94 shows the same pin with an all wood top.

Metallic pins possess the following advantages over wooden pins: Greater mechanical strength, greater durability, less liability to cause a breakdown in the line when an insulator proves defective.

Kinds of Insulators. — Advantages and Disadvantages of Glass and Porcelain. — Insulators for high-tension lines are of either glass or porcelain, or

a combination of the two. They differ widely from those used in low-tension practice, the essential points of difference being a stouter mechanical construction and special shapes and constructional features employed to enhance the insulating properties. High-tension insulators require to be of larger diameter than low-tension ones for the reason that the striking distance through the air varies from 3.5 to 6.5 inches, so that wide gaps must be provided between the circuit wires and all extraneous objects. The "creeping distance" allowed the current also has to be appreciable.

At the present time the ideal insulator for high-tension work does not exist. Some insulators are strong mechanically and weak electrically, and *vice versa*. For mechanical strength, high insulating properties, and the greatest degree of reliability under all conditions of operation, the solid porcelain insulator is preëminently superior to any other form that is now used.

In point of mechanical strength porcelain of the best grade possesses nearly double the strength of the best glass obtainable, as can be demonstrated by letting a steel ball fall from a given distance on insulators made of the two materials.

In point of insulating properties porcelain is fully equal to the best glass, and its non-hygroscopic character insures less liability from surface leakage in damp weather, or on lines near the seacoast.

Porcelain is not so brittle as glass, and an insulator may be chipped or struck with a bullet without cracking in such a way as to cause a leak. Porcelain, however, has several disadvantages. It is much more expensive than glass; defects in the construction of porcelain insulators are not

apparent to the eye, hence the necessity of making high-voltage tests to determine the quality and condition of the insulators before they are put into use. Such tests are quite tedious and necessitate the use of expensive apparatus. Furthermore, being rather conspicuous in appearance, porcelain insulators offer a fine target to mischievously inclined riflemen and the stone-throwing small boy. The shooting of insulators has become such a frequent source of trouble to some Western transmission companies that statutes have been enacted in a few of the trans-Mississippi States making it a penal offense.

For potentials as high as 30,000 volts, glass can in most instances be more advantageously employed for insulators than porcelain. The chief advantage possessed by glass over porcelain is its cheapness. In addition to this, however, glass possesses the advantage that any defects in it are readily visible to the eye, which advantage obviates the expense of testing each insulator before it is mounted on the cross-arm. The transparency of glass confers another practical advantage over porcelain, in that it does not invite insects to build nests within the insulators. Such nests are very liable to form short circuits ultimately.

The most important objections urged against glass are its lack of mechanical strength (it averages about half the strength of porcelain of the best grade), and its hygroscopic character and consequent tendency to promote current leakage through the accumulation of moisture. As an offset to this latter fault, however, it is the consensus of opinion among both glass and porcelain advocates that the static action of the current tends to dry out any moisture which may collect on either kind of insulator.

In general, glass insulators are better adapted for light lines (aluminum), and under conditions which do not require insulators larger than six or seven inches in diameter. The fact that they are giving satisfaction on circuits operating at ~~five~~ 50 kilovolts is sufficient indication that it is by no means a settled question which kind of insulator is superior, everything considered.

Combination glass and porcelain and compound insulators are now in quite extensive use on high-tension circuits. Combination insulators are built up by cementing an inner glass sheath, which contains the pinhole, to a porcelain body. In a compound insulator constructed entirely of porcelain, the upper part or body is solid, while the porcelain base is cemented in. Combination insulators have also been constructed by cementing three layers of material together, two of which are porcelain and the other of glass, or *vice versa.*

Compound and combination insulators are much easier and cheaper to construct than solid insulators, but the dielectric thus obtained lacks homogeneity, and cannot give the insulating properties of a one-piece dielectric.

In combination insulators the current stress is transmitted from porcelain to glass, or *vice versa*, so that a concentration of the stress occurs where the two surfaces meet, and these being the weakest points in the insulator, a breakdown is liable to occur there.

Compound and combination insulators also lack mechanical strength, since the contraction of the plastic material used to hold the layers together leaves cracks and gives rise to unequal strains.

Testing of Insulators. — Insulators of all kinds should be free from cracks, bubbles, and pits.

The glaze of porcelain should entirely cover the outer surface. Glaze really possesses no insulating value; its purpose is to prevent the adherence of dirt. Highest grade porcelain exhibits a polished or vitreous fracture.

When the insulators are of glass, testing is usually limited to a visual examination, followed by a few blows from a hammer to determine the soundness of the insulator.

When porcelain insulators are used, lengthy and not infrequently expensive tests must be conducted to ascertain whether the material is thoroughly vitrified, of homogeneous character, absolutely impervious to moisture, and capable of standing the voltage stress without the surface glaze. Final high-potential tests, usually equal to double the line voltage, must also be made.

A low grade of porcelain is readily manifest from the character of the fracture. The degree of porosity is most readily determined by soaking the insulators in red ink. After being washed, thoroughly vitrified porcelain shows no traces of the ink, whereas in the low-grade variety the ink is readily absorbed and cannot be washed out. Unless perfectly non-absorbent, porcelain insulators are of no value for high-tension service.

High-potential tests to determine the degree of the dielectric properties of insulators are usually made by putting a number of the insulators, inverted, in a metallic trough, which is then filled to a depth of two or more inches with brine. The saline solution should also fill the pinholes of the insulators.

A metallic rod is set in each pinhole, and all the rods are connected in series to one terminal of a high-tension transformer or group of transformers, and the metallic pan

to the other terminal. The capacity of the high-tension supply source should be adequate to furnish an appreciable current at a potential approximately double that of the potential which the insulators will normally have to withstand in practice. Each part of a compound insulator should be capable of withstanding a pressure considerably greater than it will be called upon to withstand when the entire insulator is tested. On closing the circuit, all weak and badly constructed insulators will be punctured and a shower of intensely luminous sparks will ensue.

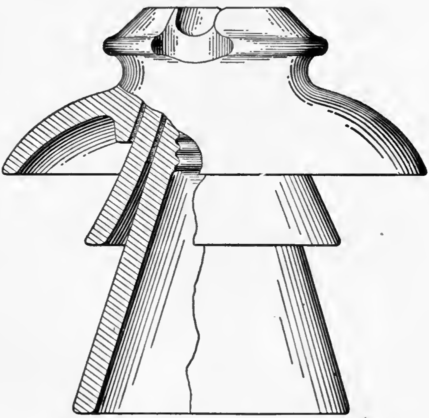


Fig. 95. A High-Tension Porcelain Insulator

Wet arcing tests should be carried out in a manner which will give approximately such conditions as exist in rain storms. Such tests can be carried out by directing a stream of water on the insulator, under 50 or 60 pounds pressure, and at an angle of from 25 to 35 degrees from the horizontal.

Types of American Insulators. — Fig. 95 shows a Locke high-tension insulator. It is of the triple-petticoat type and is constructed entirely of brown porcelain. The diameter is 11 inches and the height $10\frac{1}{2}$ inches. The pinhole is of the $1\frac{1}{2}$ inch standard, and the side and top grooves are both 1 inch.

Fig. 96 shows the Locke "Victor" type of porcelain insulator, which is used on the transmission lines of the Bay Counties Power Company, the Standard Electric Company, of California, and other high-tension circuits. It is of the triple-petticoat type and is 14 inches in diameter and $12\frac{1}{2}$ inches in height. The groove at the top in which the conductor is carried is $\frac{3}{4}$ inch wide. The insulator is designed for 60,000 and 80,000 volts.

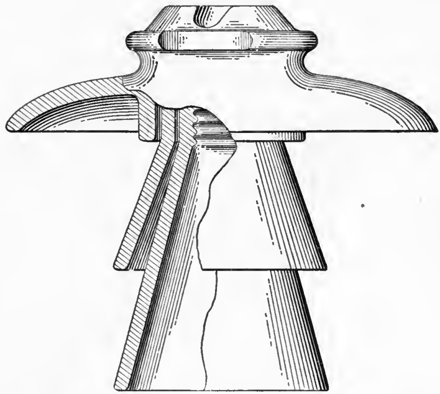


Fig. 96. Locke "Victor" Type High-Potential Insulator

Fig. 97 illustrates the "Provo" type of glass insulator made by the Hemingray Glass Company. This is the first type of glass insulator successfully used on a 40,000 volt circuit, and was first applied on the 105 mile line of the Telluride Transmission Company, of Colorado. It is of the triple-petticoat

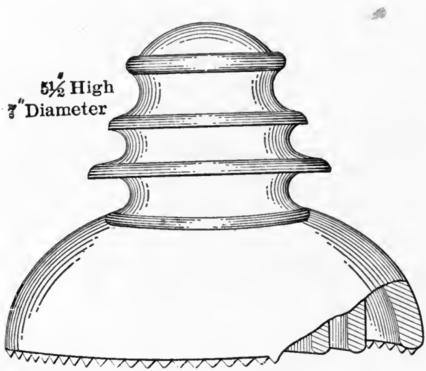


Fig. 97. A Type of High-Tension Glass Insulator

type and is 7 inches in diameter and $5\frac{1}{2}$ inches in height.

Fig. 98 shows the "Muncie" type of Hemingray glass insulator with sleeve, and Fig. 99 is a sectional sketch of the same insulator with all dimensions appended, as applied to the 57,000 volt circuit of the Missouri River Power Company. This type of insulator was designed by Mr. M. H. Gerry, Jr., chief engineer of the Missouri River Company.

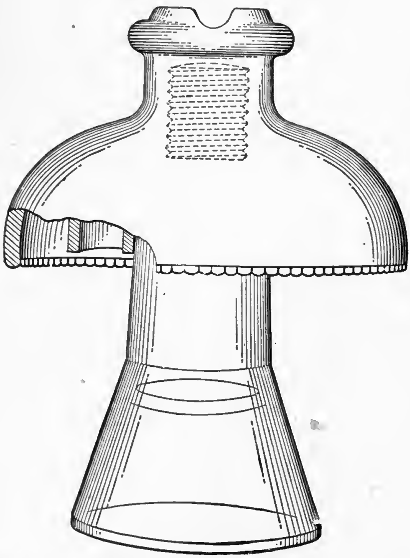


Fig. 98. Type of Glass Insulator Used on a 57,000 Volt Circuit

Devices for Fastening Conductors to Insulators. — Fig. 100 shows a Clark insulator clamp designed for use with standard insulators. It comprises two clamps which are rigidly secured to the conductor on either side of the insulator by means of a bolt and nut. The projecting ends engage the groove of the insulator and thus transfer the end strain to the insulator. The loop encircling the neck of the insulator holds the clamps firmly in position and prevents the conductor from being lifted from the groove. Fig. 101 shows the Clark interlocking insulator clamp for holding the cable or conductor in the groove of the insulator. Insulators designed

for the use of this type of clamp are made with an undercut recess on either side of the groove in the center of the insulator top, so that when the clamp is in position it is interlocked under the projecting portion in such a manner that the conductor cannot be removed or the clamp separated from the insulator without unlocking the clamp. This type of clamp is made in sizes ranging from No. 2 bare to 500,000 circular mils weather-proof wire. Fig. 102 shows the position of the clamp in the insulator. The underlocking insulator clamp (Fig. 103) is employed on transmission lines with long spans or such lines as are subject to the strains occasioned by high winds or sleet. In this type of clamp the conductor is fastened on each side of the insulator. The projections or lips engage a deep annular groove in the neck of the insulator which prevents the wire from

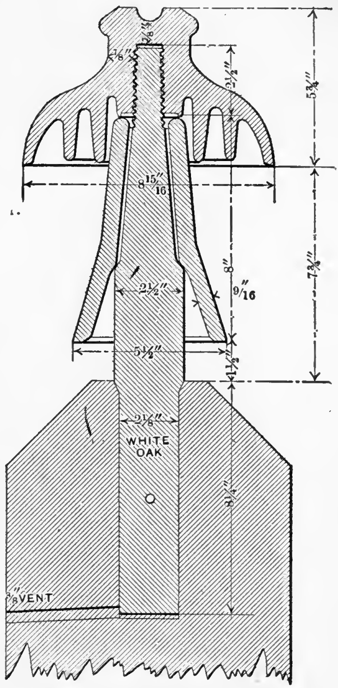


Fig. 99. Sectional View of Insulator Shown in Fig. 98

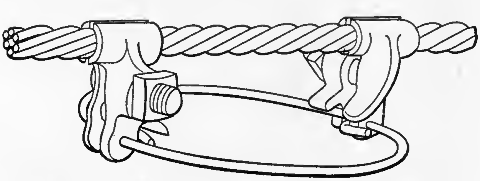


Fig. 100. Clamp for Use on Standard Insulators

being torn from the groove, and transfers the end strain over a wide area of conductor. Two such clamps are required for each insulator.

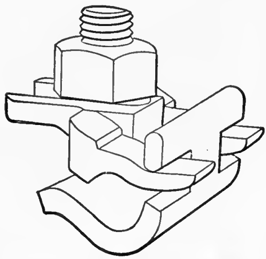


Fig. 101. An Interlocking Insulator Clamp

Methods of Stringing Wires. — Three methods of stringing wires are employed by American long-distance transmission companies, — parallel, in an isosceles triangle, and in an equilateral triangle. In parallel work the several conductors of the circuit are supported on the same cross-arm. This is the method usually adopted when two or more circuits are carried on a pole line.

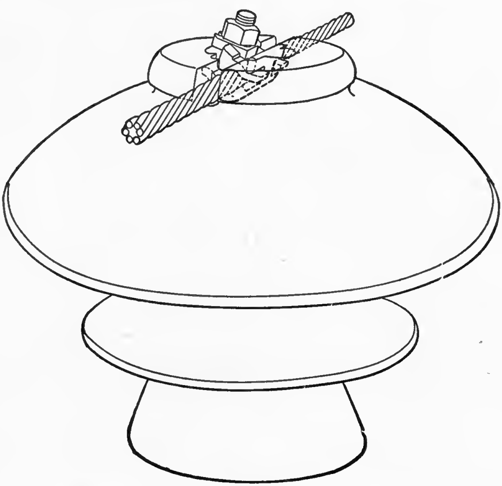


Fig. 102. Interlocking Clamp in Position

When wires are strung at the corners of an isosceles triangle two cross-arms per pole are used. This is the

general method adopted when two separate transmission lines are carried on one pole line. In this method of stringing wires the interaxial distance between the upper conductor and each of the two lower ones (assuming a three-wire circuit) is different from that between the two lower wires.

This method necessitates frequent spiraling and transpositions of the two circuits, in order to overcome unequal effects of inductance in the different legs, as well as to neutralize the mutual induction and capacity between the two lines. Means must also be adopted to balance the capacity of the separate legs of both circuits with respect to each other. Fig. 104 shows the usual method of stringing two circuits on the same pole line.

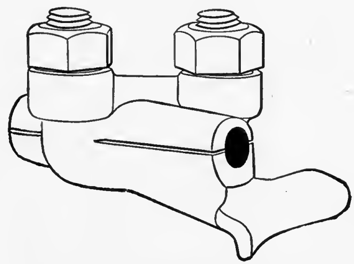


Fig. 103. An Underlocking Insulator Clamp

In three-phase transmissions with common return, which is now generally accepted as the most efficient and economical method of transmitting energy over long distances, the three conductors of a circuit are placed at points of an equilateral triangle and separated from each other by distances varying in practice from 18 to 78 inches. Fig. 105 shows a typical method of stringing conductors in the form of an equilateral triangle. The circuit in question is that of the Missouri River Power Company.

Transposition of Wires. — When two circuits are strung on one pole line, transpositions of conductors become especially important and somewhat complex, since, as pre-

viously stated, it then becomes necessary to neutralize the effect of unequal inductance in the different legs of the

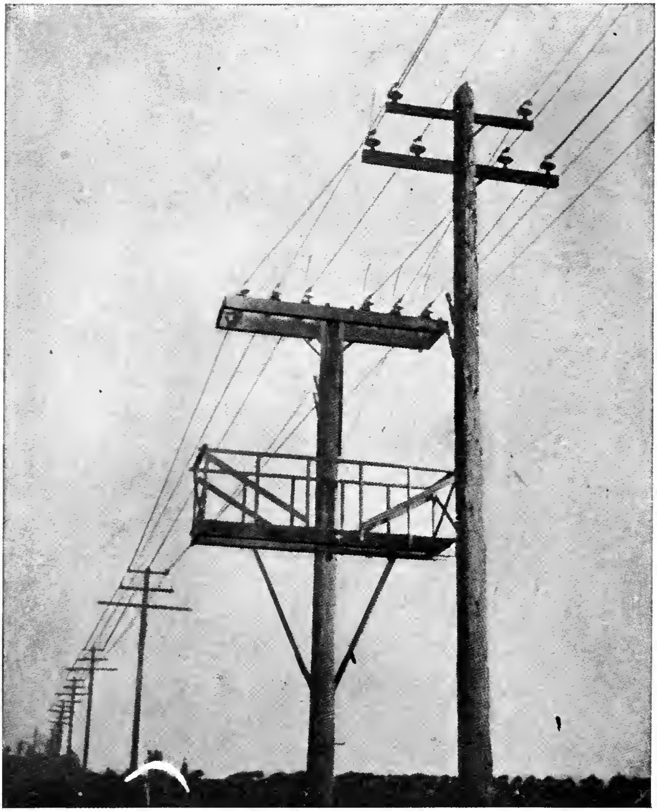


Fig. 104. Usual Method of Stringing Two Circuits on Same Pole Line

circuit (if their interaxial distances vary), and overcome mutual induction between the two lines.

The number of transpositions required on long-distance lines vary with the working conditions, such as the distance

apart of the different legs of the circuit, the number of wires on a pole line, the transmission voltage, and the proximity of telephone or telegraph wires. In American prac-

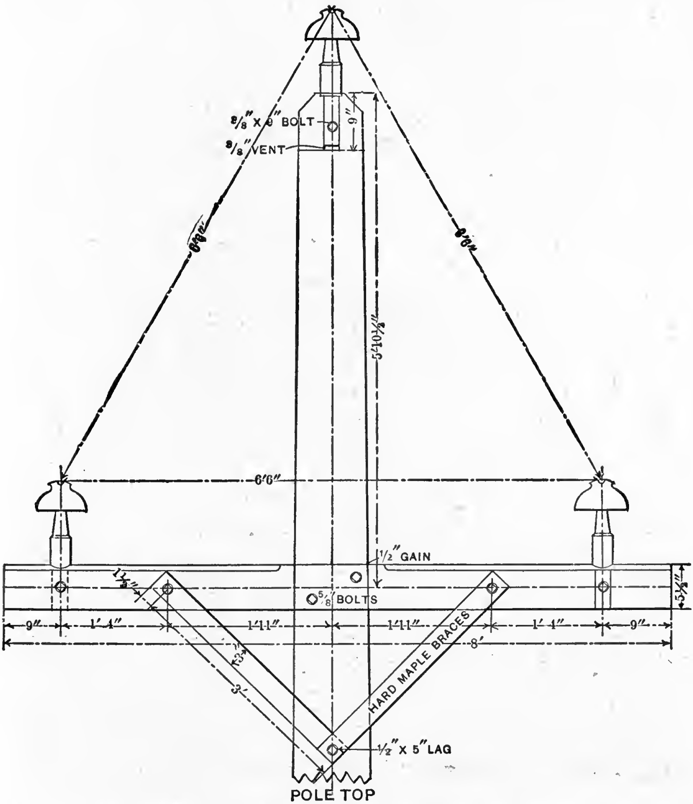


Fig. 105. Equilateral Triangle Arrangement of Conductors Used on 57,000 Volt Line of Missouri River Power Company

tice transpositions are made at distances varying from one mile up to fifteen miles.

In the equilateral triangle lay-out of wires used on three-phase circuits, the transposition of conductors is not con-

sidered absolutely necessary, unless it is impractical to carry the telephone circuit at a distance of, approximately, eight feet below the power line. With steel-supporting structures for carrying lines transpositions may be entirely dispensed with.

When telephone wires are carried on the same pole line with the power wires, and in close proximity thereto, as is frequently the case on long-distance circuits, special precautions should be taken to prevent inductance troubles.

As telephone communication is absolutely necessary between the generating and receiving stations of long-distance lines, and as economical considerations usually require that the telephone circuit be strung on the same pole line with the power circuit, the proper transposition of power and telephone wires is of the highest importance in order to prevent serious disturbances due to both electromagnetic and electrostatic effects.

Proper transposition of the telephone wires when they are carried on the same pole line with power wires is more important than the transposition of the power wires themselves; for if the telephone wires be properly transposed, the untransposed power circuit cannot set up electromagnetic and electrostatic disturbances in the telephone wires, but will produce such effects only between themselves and the ground.

Considerable care must be observed in making transpositions to avoid side strains on the line. Fig. 106 shows the usual method of transposing two three-phase circuits.

Length of Spans. — The length of span which should be used on high-tension circuits varies with the operating conditions and the factor of safety desired. No specific rules are applicable.

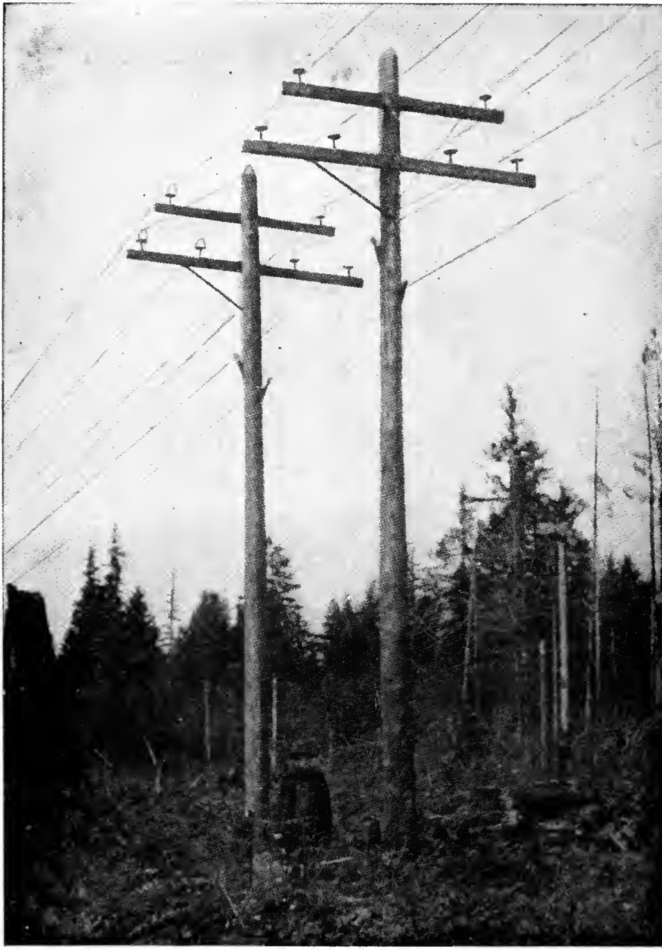


Fig. 106. Transposition of Two Three-Phase Circuits

The length of span used on copper transmission lines varies from 90 to 150 feet. Standard practice is now tending towards the use of 106 foot spans on copper lines carried on wooden poles, which makes about fifty poles per mile.

On aluminum lines the spans are frequently as long as 176 to 212 feet, requiring from 25 to 30 poles per mile. Much difference of opinion exists as to the advisability of lengthening the span of aluminum lines on account of the appreciable lightening of the weight on cross-arms and insulators secured by the use of aluminum. In most cases the advantage of lightness thus obtained should not be utilized in decreasing the line expense, but should be applied to increase the factor of safety, and the same length of span should be used for both kinds of conductors.

Protection of Transmission Lines from Lightning. — Many of the troubles to which high-tension lines are subject are due to the effects of lightning. The extent to which long-distance circuits suffer from lightning disturbances varies with the climatic conditions of the region which a line traverses, being much more severe in semi-tropical, tropical, and mountainous regions than in northerly countries.

The problem of effectively protecting high-potential lines from the destructive effects of lightning is one that has not as yet been completely solved. In fact, the capricious action of lightning often entirely sets at naught the safeguards provided to protect the lines.

Lightning generally affects an aerial line in three different ways, — by direct stroke, by induced charges, and by electrostatic induction.

Disturbances due to direct strokes of lightning are of rare occurrence. In such cases no arrester in existence can completely neutralize the effects of it on the line.

Induced discharges caused by the electromagnetic effect of a lightning flash are a frequent source of trouble.

Electrostatic charges giving rise to electrostatic induction are due to charges in the surrounding atmosphere.

Since a lightning discharge is of enormously high frequency, inductance in the line opposes a very high impedance to a discharge, and the discharge takes the shortest and most direct passage to ground. This accounts in a large measure for the puncturing of transformer coils.

Since inductance in the line offers great resistance to the passage of a lightning discharge this fact is sometimes taken advantage of by putting choke coils in series with the line, and between the arrester and the central station. Such choke coils are made of flat copper strip, wound on a non-conducting core, the separate layers being insulated with mica.

This combination described works fairly satisfactory as a protecting device for the station apparatus, but its cost makes its use prohibitive on every line arrester unless it is imperative to give the utmost possible protection to the apparatus.

Practice differs as regards the use of arresters at various points along high-tension lines. Some transmission companies use arresters only in the generating station and at sub-stations. To safeguard a circuit effectively, arresters should be located at the ends of all lines, at sub-stations, and at points where the lines branch off.

Many transmission companies rely partly or wholly upon

a grounded wire along the lines as a safeguard against damage by lightning. Such wires are made of either smooth galvanized iron in the solid or cable form, or in the shape of barbed wire, and strung parallel to the power wires and grounded at intervals. Such a grounded wire constitutes a short-circuited secondary, which largely absorbs by induction the energy of a lightning discharge to the line. A grounded wire strung near power wires also serves to discharge any charged atmosphere which may blow across the line.

Another advantage is afforded by a grounded parallel wire in cases where transmission lines run through mountainous regions, in which there are marked differences in the altitude of different parts of the line. Under such conditions there is an electrostatic effect due to differences in altitude, which produces an appreciably greater difference of potential between conductors and the ground in the low than in the high altitudes.

When parallel grounded wires are depended upon for protection, three such wires are usually employed, one wire being strung on top of the pole, and one at each end of the cross-arm. In order to give them reliable mechanical support they are usually mounted on pony insulators.

Frequent grounding is necessary in order that the opposition to the flow of current between the grounded wire and the earth will be reduced to a minimum.

Surges in Transmission Lines. — The chief causes of surges in high-tension circuits are opening a line carrying a load or under a short circuit, closing a high-potential line switch to charge the line, and opening a high-tension switch to make the line dead.

The worst cases of damage to apparatus by surges are those produced by the sudden rupture of a short circuit. This is due to the fact that the current which the line is carrying at the time of the short circuit is considerably in excess of the maximum normal operating current; the magnitude of alternating-current surging depends upon the value of the current at the instant of rupture.

If the interruption takes place at the zero point of the current wave, the surge which follows is slight enough to be considered negligible, but if the interruption occurs at the peak or crest of the current wave the surging has a value which is the same as that which would be produced by a direct current of the same strength.

If the conditions of operation render it possible to break the short circuit gradually through external resistance, the surging will not be of appreciable importance. The surging will also be slight if the current wave can be stopped by automatic means at or very near its zero point.

When the line switch is first closed on a dead line, charging current at once flows into the line, which is a simple condenser. But this charging current is obliged to flow through the line inductance, and this stores up energy in the shape of a magnetic field. The stored-up energy then discharges into the condensive line and so adds to the charge already in it. The maximum possible E.M.F. from this cause is double the working potential of the line.

In opening a line switch to disconnect a circuit, the condenser of the circuit discharges across the terminals of the switch the instant they are separated; and owing to the charging current of the condenser, the pressure of the circuit rises to its maximum value of operation at the normal frequency of the line.

Hence before the switch can be pulled very far apart, the line pressure set up by the oscillating current in the circuit is superposed on the pressure between the switch terminals due to the generator. Such increase of potential may cause the arc to oscillate several times between the switch jaws before the circuit becomes absolutely dead.

The surge following the opening of a high-tension line may cause a rise of potential equal to double the normal operating pressure.

Very great precautions should be exercised in opening a high-potential circuit under load, as destructive voltages are liable to ensue.

When an alternating current is suddenly interrupted at the receiving end of a line its natural outlet is suppressed. It at once flows into the condenser and charges the circuit, but since the condenser cannot hold the charge, it discharges into the self-inductance of the line, and the energy is converted into magnetic energy.

The magnetic field then gives up its energy to the condenser, and the cyclical exchange of energy is repeated in gradually decreasing amplitude until the line resistance has consumed the energy at first stored in the line self-inductance.

The surges or oscillatory currents set up in this way are of a very serious character, and may completely destroy or at least severely strain the insulation of the generating or the transforming apparatus, or both.

Losses by Leakage and Electrostatic Induction. — Aside from the difficulties of effectively insulating the line, the limitations to the potentials practical for electric power transmission are losses by line leakage and electrostatic induction.

Leakage losses take place from wire to wire of the circuit, and with very high potentials may reach enormous values, unless the conductors are made unduly large and are widely separated.

A very interesting series of experiments were carried out by Mr. Charles F. Scott, to ascertain the losses by leakage on high-tension circuits and the limitations to long-distance power transmissions. The results of his experiments may be thus summed up: The power loss through the air by current leakage between wires increases with the impressed voltage, and after a critical voltage is reached it increases very rapidly. With a given impressed voltage the loss decreases as the distance between wires is increased. The loss is not appreciably affected by atmospheric conditions, such as rain, snow, or humidity. Peaked E.M.F. wave shapes give greater losses than flat-topped waves. The loss decreases as the diameter of the wires increases.

His results were summed up in a set of curves, reproduced in Fig. 107, showing the relations between wire distance, operating voltages, and power loss. Fig. 108 shows the loss when the distance between conductors was increased to 48 inches.

Dr. Steinmetz found in his experiments on the electric disruptive strength of powerful solid dielectrics that the atmosphere surrounding the solid dielectric specimen and the electrodes applied thereto would rupture under the strain produced by the flux of electric force through it much easier than the solid dielectric. This produces envelopes of conductive atmosphere around the electrodes and over the surface of the strong dielectric, which phenomenon resembles a brush discharge from a static machine, and is

termed the *corona.* Corona formation depends primarily upon the maximum, and not upon the effective value of the E.M.F. wave, as has been shown by the experiments of Scott, Mershon, Ryan, etc.

The experimental work of Steinmetz has also shown that the atmosphere conducts after disruption in two forms, either arcs or intensely heated streamers at high-current

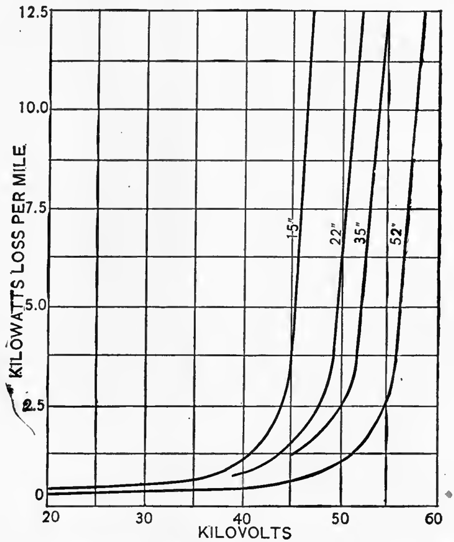


Fig. 107. Curves Showing Power Losses at Various Voltages and Spacings of Wires

density, or coronal or brush discharges at lower current density. The latter begin to appear at pressures above 40,000 volts. Steinmetz further ascertained that the dielectric strength of the atmosphere in bulk requires approximately a potential gradient of 10,000 effective volts per inch, with an E.M.F. wave following the sine law.

The researches of Professor Ryan (Trans. A. I. E. E. Vol. 21) show that the critical voltage of a brush or coronal discharge is a function of the barometric pressure of the air: his equation for this is

$$K_v = 0.902\, b + 2.93,$$

where K_v = effective kilovolts and b = barometric pressure in inches of mercury.

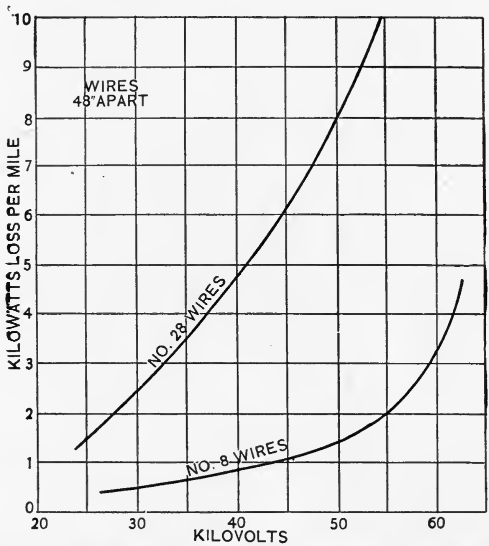


Fig. 108. Curves Showing Losses with Wires 48 Inches Apart

LIBRA OF TH UNIVER OF CALIFO

Hence on lines crossing high altitudes the pressures which are permissible are appreciably less than those which the same line construction admits of at sea level.

Danger of brush discharge becomes less as the size of the conductor increases. A large conductor therefore permits the use of higher voltages than a small one, and

aluminum conductors diminish the tendency of coronal discharges.

The equation, according to Professor Ryan, which gives the maximum voltage causing corona formation, is,

$$E_{max} = \frac{17.94\, b}{459 + t} \times 2055\, (r + d) \log_{10} \left(\frac{s}{r}\right) D' \times 10^{10}$$

where E_{max} = maximum value of the potential wave impressed upon the line.

b = barometric pressure in inches of mercury.

t = temperature in degrees Fahr.

s = separation of line conductors from center to center, in inches.

d = distance from conductor surfaces at which the strain due to the electrostatic field causes rupture of the atmosphere.

D' = the dielectric flux density, in coulombs per square inch, that will electrically rupture the atmosphere at distance d from the surface of the conductor having a radius r.

"For wires of 0.25 inch in diameter and upwards, D' and d remain constant at

$D' = 170 \times 10^{-10}$ coulombs per square inch and
$d = 0.07$ inches."

Hence for such wires Ryan's equation becomes,

$$E_{max} = \frac{17.94\, b}{459 + t} \times 350{,}000\, (r + 0.07) \log_{10} \left(\frac{s}{r}\right).$$

Grounding of High-Potential Lines. — Grounding the neutral point of a high-tension line is desirable for the following reasons: When the neutral point is grounded the voltage between the conductors and the ground is limited to the operating potential of the line. In an ungrounded line, the voltage between phase conductors and ground

may vary between wide limits, and may attain such values that the liability to the breakdown of the line insulation becomes serious. When a high-potential line is grounded, it insures the immediate detection of faults and necessitates their immediate removal.

One objection to grounding is that it increases the element of danger to persons and property. It is the general opinion that the fact of the conductor voltages being maintained at a definite and dangerous value above the ground potential is sufficient proof that the danger to life is greatly augmented by the practice.

As an illustration: If the neutral is grounded, the operating Y-pressure of the system is introduced between any line wire and the ground, and on making a contact to ground, a body touching this contact would be subject to this pressure.

Hence if capacity were not present, grounding the neutral point would augment the element of danger; but since capacity is always present to a greater or less degree, each wire is really grounded through a condenser. And although the conditions are slightly different from the case of one conductor grounded direct, the results are nearly alike.

Thus the action of these capacity connections to ground will be to cause the E.M.F.'s to concentrate themselves about the point of earth potential.

And so when the line wires have a capacity effect, there are differences of potentials between them and the ground, even with no part of the system grounded direct. Such differences of potential will not be neutralized by connecting the conductor to ground through resistance, since the capacity behaves like an elastic band, and tends to check

the displacement of the conductor E.M.F.'s relative to the earth.

However, the difference of potential will be diminished by the flow of current through the resistance, and when the current is of considerable strength, may be reduced to a non-dangerous value.

The effect in any particular case will depend upon the value of the capacity in the several wires, and also upon the resistance of the grounding substance.

Maintenance of Pole Lines. — Patrolling of high-tension lines becomes essential in direct proportion to the potential employed for transmission, and the difficulties of operation. Current practice as regards the patrolling of lines differs quite widely. Some companies have their lines patrolled daily, some weekly, while others do so only at intervals of one or several months. The character of the country which the line traverses is an important factor in determining the frequency for making inspections.

The necessity for patrol trips is considerably obviated by the use of telephone lines on the same poles with the transmission circuits. When a short circuit or a dangerous leakage has occurred on the power circuit, the peculiar sounds given out by the telephone receiver render the fact of its occurrence unmistakable.

On circuits where patrolling is carried out the line is divided into sections varying from 10 to 20 miles in length, each of which is assigned to a patrolman. In order to enable the patrolman to make reports to the central station, taps are brought down from the telephone circuits to booths located a few miles apart, to which the patrolman makes connection with his portable telephone set and informs the station attendants of the condition of

the line. As a precaution against the danger of a high-voltage discharge through the telephone line, each booth is provided with a highly insulated stool upon which the trouble man sits in calling up the central or sub-station.

Calculation of a 75 Mile Three-Phase Transmission Line. —

Data: 2,000 k. w. with line loss of 3 per cent.
25 ∼ Frequency.
.85 Power Factor.
Copper Conductors.

Assume 30,000 volts as the pressure of transmission and consider one leg of the circuit.

Then $\frac{30{,}000}{\sqrt{3}} = 17320$ volts = E.M.F. between any wire and the neutral point.

$$\text{Cos } 30^\circ = \frac{15000}{h} = \frac{\sqrt{3}}{2}$$

$$h = \frac{15000 \times 2}{\sqrt{3}} = 17320$$

The energy delivered by each leg is

$$\frac{2060 \text{ k.w.}}{3} = 686.6 \text{ k.w.}$$

The apparent energy delivered by each leg is

$$\frac{686.6 \text{ k.w.}}{.85} = 808{,}000 \text{ watts}$$

The current in each leg is

$$\frac{808000}{17320} = 46.6 \text{ amperes.}$$

To determine the size of conductor necessary, assume the limit of the *IR* drop to be 10 per cent of the voltage in each leg:

10 per cent of 17320 = 1732 volts.

Hence,

$$R = \frac{1732}{46.6} = 37.2 \text{ ohms.}$$

And the ohms per 1,000 feet are,

$$\frac{37.2}{5.28 \times 75} = 0.965 \text{ ohms per 1000 ft.}$$

(5.28 is the ohms per mile of wire.)

Therefore, we use No. 00 wire whose radius R is 0.78 per 1,000 feet by table.

And the total resistance of one leg is

$$0.78 \times 75 \times 5.28 = 30.9 \text{ ohms.}$$

The inductance of one leg per mile is

$$L \text{ (in henrys)} = \left[80.5 + 740 \log\left(\frac{d}{R}\right)\right]^{10^{-6}}$$

$$d = 18 \text{ inches} = 45.8 \text{ cms.}$$

$$R = \frac{.365}{2} 2.54 = .462 \text{ cms.}$$

$$L = \left(80.5 + 740 \log \frac{45.8}{.462}\right)^{10^{-6}}$$

$$= (80.5 + 740 \log 99.3)\ 10^{-6}$$

$$= (80.5 + 740 \times 1.996949)\ 10^{-6}$$

$$= \frac{80.5 + 1470}{1{,}000{,}000} = \frac{1550.5}{1{,}000{,}000} = .00155$$

in henrys per wire per mile.

The total inductance of each leg is

$$.00155 \times 75 = .117 \text{ henrys.}$$

The inductance in ohms is

$$2\,\pi f L = 2 \times 3.14 \times 25 \times .117 = 18.4 \text{ ohms.}$$

The capacity of the line in microfarads is

$$C = \frac{.0776\,L}{2 \log_{10} \frac{d}{r}} = .0094$$

where

L = length of line in miles.
d = distance between wires in inches.
r = radius of wire in inches.

$$C = \frac{.0776 \times 75}{2 \log_{10} \frac{18}{.182}} = \frac{5.82}{2 \log 99} = \frac{5.82}{2 \times 1.9956}$$

$$= \frac{5.82}{3.990} = 1.46 \text{ microfarads.}$$

$$C \text{ in farads} = 1.46 \times 10^{-6} = .00000146.$$

The charging current per wire per leg is

$$I_c = \frac{E \times C \times 2\,\pi \times f}{\sqrt{3} \times 10^6}$$

where

E = E.M.F. between wires.
f = frequency.
C = capacity in microfarads between one wire and the neutral point.

Hence

$$I_c = \frac{17{,}320 \times 1.46 \times 2 \times 3.14 \times 25}{\sqrt{3} \times 1{,}000{,}000} =$$

.405 amperes per wire per line.

The E.M.F. required to force this charging current through each leg is

$$E_c = \frac{I}{2\,\pi f C}.$$

$$\therefore E_c = \frac{.405}{2 \times 3.14 \times 25 \times .00000146} = 4350 \text{ volts.}$$

The charging current drop is 1,760 volts.

And the drop due to charging current plus the load current is

$$E_{c+l} = 46.3 \times 30.9 = 1430 \text{ volts drop.}$$

The drop due to inductance is

$$E_L = 2\,\pi f L I = 18.4 \times 46.3 = 852 \text{ volts.}$$

Explanation: E and I differ in phase by 31°, while I_c and E_c are 90° ahead of E. Taking the resultant of I and I_c, one gets I_{c+i}, in phase with E_c.

Finding, by trigonometry, the angle between this E_c and E, multiplying this by the cosine and combining the result with E_L.

90° ahead of this E_c is E. Finding the angle between E and E_L we take its cosine and resolve E_L on E.

The result is the total E.

$$\begin{array}{rl} 179^\circ & - 60' \\ 121 & - 45 \\ \hline 58^\circ & - 15' = C \end{array}$$

$$\text{Cos } A = \frac{b^2 + c^2 - a^2}{2\,bc} = \frac{2171 + 2170 - .164}{2 \times 46.6 \times 46.3}$$

$$= \frac{4300 \times 488}{4315 \times 16} = .9965$$

$$A = 4^\circ \; 45'$$

$$B = \phi - A = 31^\circ \; 45' - 4^\circ \; 45' = 27^\circ$$

$$D = 90^\circ - B = 63^\circ$$

and

$$I_{c+l} = C = \sqrt{a^2 + b^2 - 2\,ab\cos C}$$
$$C = 58° \quad 15'$$
$$a = .405$$
$$b = 46.6$$

Then

$$I_{c+l} = \sqrt{.164025 + 2171.56 - 37.8 \times .5262}$$
$$= \sqrt{.164025 + 2171.56 - 19.8}$$
$$= \sqrt{2151.9}$$
$$= 46.3 \text{ amperes for } I_{\text{capacity + load current.}}$$
$$\text{Cos } 63° = \text{Cos } D = .4540$$
$$\text{Cos } 27° = \text{Cos } B = .8910$$

Fig. 109 is a vector diagram showing the magnitude of the various quantities in the above calculation.

Combining the volts vectorially one gets (Fig. 110)

$$E_L \times \text{Cos } 63° = 852 \times .4540 = 386.8$$
$$E_{\text{capacity + load}} \times \text{Cos } 27° = 1430 \times .891 = 1274.1$$
$$E_{\text{total}} = 17320 + 1274.1 + 386.8 = 18981$$
$$I_{\text{total}} = 46.3 \text{ amperes.}$$

The above calculations are for one leg of the circuit, and the voltage is considered between one wire and the neutral point.

Multiplying this voltage (18,981) by the $\sqrt{3}$ we obtain 32,820 as the total line voltage.

The true power factor is

$$\text{Cos } 27° = .891.$$

The regulation of the line is

$$32820 \div 30000 = 9.4 \text{ per cent.}$$

Then kilowatts at generator =

$$\frac{32820 \times 46.3 \times 89.1 \times 3}{1000 \times \sqrt{3}} = 2350 + 3 \text{ per cent}$$
$$= 2450 \text{ kilowatts at } 89.1 \text{ per cent power factor.}$$

Using a 1 to 6 step-up transformer the E.M.F. of the generator will be 5,500 volts.

And the current, $\frac{2450 \times 1000}{5500} = 445$ amperes.

OR SOLVING VECTORIALLY ONE GETS

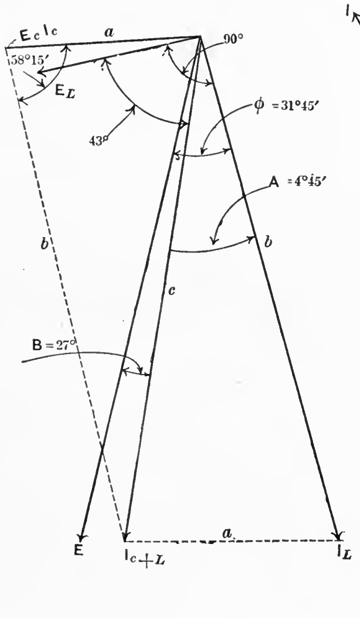


Fig. 109

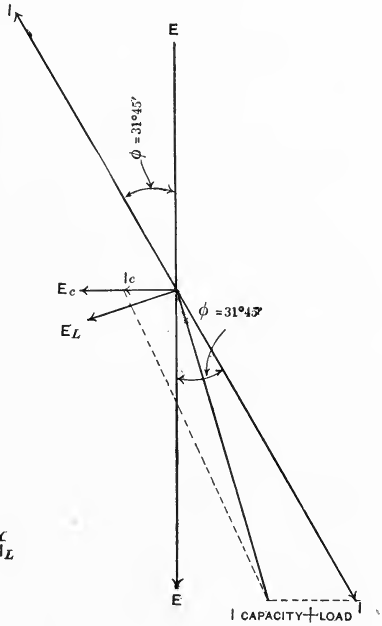


Fig. 110

Generator specifications:

3-phase alternator of revolving field type.	445 amperes
	25 cycles.
2,450 k.w. or 3,290 h.p.	94 r.p.m.
5,500 volts.	32 poles.

To be direct connected to an impulse water-wheel of 3,560 h.p. output, which allows for $92\frac{1}{2}$ generator efficiency.

BIBLIOGRAPHY

Electrical Conductors. — Perrine. D. Van Nostrand Co. New York. 1902.

Data Relating to Electrical Conductors and Cables. — Fisher. Proceedings American Institute Electrical Engineers, Vol. 24, p. 687.

The Use of Aluminum Line Wire and Some Constants for Transmission Lines. — Perrine and Baum. Transactions American Institute Electrical Engineers, Vol. 18, p. 391.

Mechanical Specifications for a Proposed Insulator Pin. — Mershon. Transactions American Institute Electrical Engineers, Vol. 20.

Burning of Wooden Pins on High-Tension Transmission Lines. — Chesney. Transactions American Institute Electrical Engineers, Vol. 20, p. 435.

Testing of Insulators. — Blackwell. Transactions American Institute Electrical Engineers, Vol. 20.

Overhead High-Tension Distributing Systems in Suburban Districts. — Lukes. Transactions American Institute Electrical Engineers, Vol. 21, p. 25.

Methods of Bringing High-Tension Wires into Buildings. — Skinner. Transactions American Institute Electrical Engineers, Vol. 20, p. 1171.

Transposition and Relative Location of Power and Telephone Wires. — Lincoln. Transactions American Institute Electrical Engineers, Vol. 20.

The Protection of Telephone or Telegraph Wires When in Hazardous Proximity to High-Tension Lines. — Chetwood. Electrical World and Engineer, New York, May 21, 1904, p. 968.

The Prevention of Crosses between Signalling and High-Voltage Circuits. — Knowlton. Electrical World and Engineer, New York, April 23, 1904, p 768.

The Grounded Wire as a Protection against Lightning. — Mershon. Transactions American Institute Electrical Engineers, Vol. 20, p. 1180.

Grounding of High-Potential Systems. — Nies. Electrical World and Engineer, April 12, 1902, p. 639.

Theoretical Investigations of Some Oscillations of Extremely High Potential in Alternating High-Potential Transmissions. — Steinmetz. Transactions American Institute Electrical Engineers, Vol. 18, p. 383.

The Regulation of Transmission Lines. — Lighthipe. Transactions Pacific Coast Transmission Association, San Francisco, July, 1904.

Possibilities of Single-Phase Currents in Electric Power Transmission. — Ballard and Sprout. Transactions Pacific Coast Transmission Association, San Francisco, July, 1904.

Medium Span Line Construction. — Copeland. Transactions Pacific Coast Transmission Association, San Francisco, July, 1904.

Resonance in Aerial Systems. — Physical Review, New York, Vol. 18, pp. 200–208.

Surges in Transmission Circuits. — Kennelly. Electrical World and Engineer, New York, Nov. 23, 1901, p. 847.

Atmospheric Losses on High-Voltage Lines. — Scott. Transactions American Institute Electrical Engineers, Vol. 15, p. 531.

High-Power Surges in Electric Distribution Systems of Great Magnitude. — Steinmetz. Proceedings American Institute Electrical Engineers, Vol. 24, p. 575.

An Experimental Study of the Rise of Potential on Commercial Transmission Lines Due to Static Disturbances. — Thomas. Proceedings American Institute Electrical Engineers, Vol. 24, p. 705.

The Conductivity of the Atmosphere at High Voltages. — Ryan. Transactions American Institute Electrical Engineers, Vol. 21, p. 275.

Guard Wires for Transmission Lines. — Electrical Review, Jan. 16, 1904.

Losses by Electrostatic Discharge on High-Tension Lines. — Electrical World and Engineer, July 21, 1900, p. 91.

On the Mechanism of Electric Power Transmission. — Electrical World and Engineer, New York, Oct. 24, 1903, p. 673.

Drop in Alternating-Current Lines. — Mershon. American Electrician, New York, June, 1897.

CHAPTER VII

TRANSFORMERS

A TRANSFORMER is an alternating-current device for changing electric energy of one electromotive force into the same electric energy at a different electromotive force. It consists of one magnetic circuit and two electric circuits, which are so interlinked with it that current traversing the primary electrical circuit sets up an alternating flux in the magnetic circuit which induces an alternating E.M.F. in the secondary circuit. The value of the alternating E.M.F. so induced is dependent upon the ratio of the numbers of turns in the primary and secondary windings. Hence, the ratio of transformation is the ratio of the number of turns in the secondary to the number of turns in the primary.

If this ratio is greater than unity, the transformer is termed a "step-up" transformer, for the reason that it delivers energy at a higher potential than it is received. If this ratio is less than unity, the transformer becomes a "step-down" translating device, since it delivers energy at a lower pressure than the primary received pressure. It is obvious that in high-tension transmission of power the step-up transformer finds its principal use at the generating end, owing to the limited potential which alternators are capable of giving, 15,000 volts being the highest pressure for which commercial alternators have been wound up to the time of writing.

The step-down type is used at the receiving points in a circuit where currents of particular potentials are necessary

for the peculiar characters of apparatus in use on distribution circuits.

Losses in Transformers. — Transformer losses are made up of (1) Resistance of the electric circuits; (2) hysteresis in the iron; (3) eddy currents in the iron. These losses are divided into "copper" and "core" losses. The copper loss is due to the resistance of the primary and secondary windings, while core losses are those due to hysteresis and eddy currents in the iron of the magnetic circuit. Copper losses also properly include eddy current losses, but such losses are in most cases small enough to be considered negligible or else are combined with the eddy current losses in the core.

The magnitude of the copper loss is equal to the product of the square of the current times the ohmic resistance of the wire. Calling the copper loss in watts P_c; I_p the current in the primary, and I_s the current in the secondary; and R_p and R_s the primary and secondary resistances respectively, then

$$P_c = I_p^2 R_p + I_s^2 R_s$$

from which it is evident that the copper loss varies as the square of the load in amperes.

The copper loss also depends largely on the design of the transformer and the conditions of its operation. A well-designed transformer of one kilowatt output will have a copper loss of from 2.5 to 3 per cent. For 100 kilowatt sizes the copper loss is approximately 1 per cent of the output.

Copper losses increase with the resistance, and the resistance increasing with rise of temperature makes the loss larger when the transformer becomes heated by the current or by extraneous sources of heat. The permissible rise in

temperature of a transformer is 50° C. above the surrounding air, according to the American Institute of Electrical Engineers' standard code. The resistance of the windings of a transformer increases about 0.004 ohm for each degree rise of temperature.

Copper losses affect a transformer in three ways: (1) The efficiency is reduced; (2) the resistance gives rise to heat which may damage the insulation; (3) if of the constant potential type the regulation of the transformer is seriously affected.

Hysteresis Loss. — A certain number of watts are necessary to carry the iron through cyclic changes of magnetization, causing a loss of energy which by Steinmetz's equation is,

$$P_h = 10^{-7} VfNB_m^{1.6}$$

in which

P_h = loss in watts.
V = volume of core in cubic centimeters.
f = frequency (cycles per second).
N = a hysteretic constant.
B_m = maximum flux density per square centimeter.

That component of the impressed E.M.F. which is necessary to overcome the hysteretic loss is

$$E_h = \frac{P_h}{I_p},$$

and is in phase with I_p.

Core losses differ from copper losses in that they are nearly constant for all loads, while the latter vary as the square of the load. (In the constant-current type of transformer the converse holds true, *i.e.*, the copper loss in the secondary is constant, while the iron loss varies with the load.)

The magnitude of the core loss is also governed by the shape of the impressed E.M.F. wave, a peaked wave form giving a slightly lower core loss than a flat-topped wave. Beyond a definite limit, however, the wave form may be so flat that the core loss may be greater than that which would be given by a true sine curve E.M.F.

In the best types of commercial transformers the core loss for 60 cycles may be about 70 per cent hysteresis and 30 per cent eddy current loss. At 125 cycles it will average 55 per cent hysteresis and 45 per cent eddy current loss.

In most commercial transformers the copper and core losses are almost equal at full load. In cases where constant voltage is imperative, or when the transformer is operated constantly under heavy load, the copper loss is frequently reduced at the expense of the iron loss.

Eddy or Foucault Current Losses. — These are caused by small currents eddying in the iron of the transformer. The E.M.F. giving rise to eddy currents is in phase with the counter E.M.F. of the primary, since both are due to the same flux.

These eddy currents cause a loss of energy due to the heating which they produce in the iron. To reduce this loss to a minimum the cores of transformers are constructed of thin laminæ of iron, which are japanned or lacquered on each side. In the construction of a transformer these laminæ are so placed that they are transverse to the direction of flow of the Foucault currents, but are longitudinal to the path of the magnetic flux.

The loss in watts from Foucault currents is

$$P_e = bvJ^2t^2B_m^2$$

where

P_e = loss in watts.

b = constant depending upon the specific resistance of the iron. $= 10^{-16}$

v = volume of the iron in cubic centimeters.

f = frequency (cycles per second).

t = thickness of the laminæ in centimeters.

B_m = maximum flux density per square centimeter.

Eddy current losses are for all practical considerations independent of the load.

Capacity of Transformers. — The maximum output for which transformers can be designed is limited by several necessary conditions of operation. When the secondary current is increased the secondary E.M.F. of the transformer decreases, and the energy output increases with the current, and becomes a maximum. Thus the maximum power output becomes the maximum limit to the capacity of the transformer. But under commercial conditions the capacity of a transformer is limited to a considerably smaller value than this maximum capacity since:

(1) If the rise of temperature is not kept within a certain limit, damage to insulation will occur and breakdowns are liable to ensue.

(2) In practice it is generally essential that constant secondary E.M.F. be maintained.

(3) At excessive outputs transformer efficiencies are greatly reduced.

The radiation surface per watt per degree rise of temperature of small transformers is relatively large, and their output is, in general, limited only by the requirements of close regulation. In large transformers the radiating surface per watt per degree rise of temperature is relatively small, and

their capacity is hence limited by the allowable rise in temperature.

The larger the output of transformers up to a certain limit, the closer is their regulation and the higher their efficiency.

The capacities of transformers used in high-tension practice vary from a few kilowatts up to as high as 7,500 kilowatts, which is the largest size that has been thus far designed for commercial operation.

Efficiencies of Transformers. — The efficiency of a transformer is the ratio of its net power input to the gross power output; or, in other words, it is the ratio of the power output to the power input plus all losses.

Hence the efficiency of a transformer is

$$\epsilon = \frac{E_s I_s}{E_s I_s + P_h + P_e + P_c}$$

where E_s is the difference of potential at the secondary terminals, and I_s is the current in the secondary; and P_h, P_c, and P_e are the losses in watts due to hysteresis, resistance, and eddy currents respectively.

In large transformers used in high-tension practice, the denominator of the efficiency equation is also increased by the power consumed by the device employed in keeping down its temperature, such as the energy consumed in running blowers for air-blast transformers, and in operating the motor-driven pumps for oil or water-cooled transformers.

In cases where one blower or other cooling apparatus supplies a bank of transformers, allowance should be made for the percentage of energy supplied to each in keeping it cool.

Sinçe transformer losses are largely governed by the

temperature, the efficiency can only be accurately determined by bearing in mind some definite temperature (usually 25° C.).

The all-day efficiency of a transformer is the ratio of the energy output to the energy input during twenty-four hours. In practice this efficiency is calculated on the assumption of nineteen hours of no load and five hours of full load. This applies only to lighting transformers.

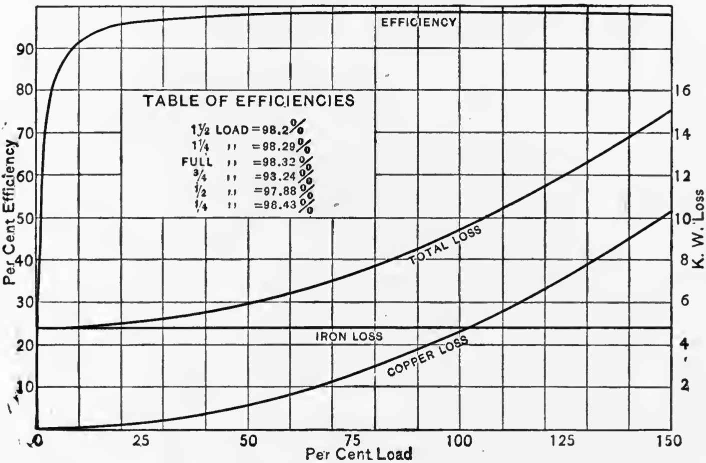


Fig. 111. Efficiency Curves of a 550 K.W. Transformer

The efficiency of a transformer is always measured at non-inductive load and at the rated frequency, unless otherwise specified. Fig. 111 shows efficiency curves of a 550 k.w. transformer.

Testing of Transformers. — It is generally necessary to make a certain number of tests upon a transformer to ascertain whether it is fulfilling the required specifications and giving its rated efficiency. The tests usually made have for their purpose determination of the following val-

ues: (1) Core Loss and Leakage Currents; (2) Copper Loss; (3) Resistance; (4) Impedance; (5) Heating; (6) Insulation; (7) Efficiency.

In determining the core loss and leakage current, an alternating current of the rated secondary pressure and frequency is applied to the secondary terminals, and an ammeter and wattmeter are connected in the circuit to read the leakage current and core loss respectively. To ascertain the leakage current the reading of the ammeter should be divided by the ratio of transformation. From the data obtained in this test the no-load power factor is readily calculated.

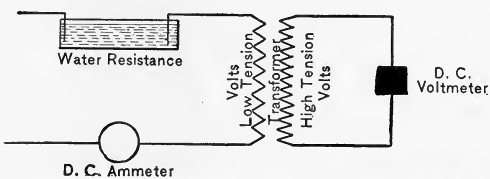


Fig. 112. Connections for Scott Method of Hysteresis Measurement

Fig. 112 shows the connections for applying C. F. Scott's method of measuring the hysteresis loss in large transformers. When a direct current is sent through the low-tension winding a magnetic field is set up in the iron. With a gradual increase or decrease of current, the strength of the magnetic field will be proportionately increased or decreased, and this varying field induces an E.M.F. in the transformer winding which is measured by the voltmeter across the high-tension terminals. With a uniform rate of change in the magnetic field there is a constant E.M.F. generated in the winding, and the voltmeter pointer remains stationary.

Commencing with zero current the resistance is cut out in such steps as will give a steady deflection of the voltmeter. As soon as the maximum desired induction is attained the voltmeter is reversed and the current gradually decreased to zero. The current is then reversed and gradually increased to a negative maximum; then the voltmeter is again reversed and the current decreased to zero, completing the cycle. It is necessary to bring the iron "into step" before making readings, by running it through several complete cycles.

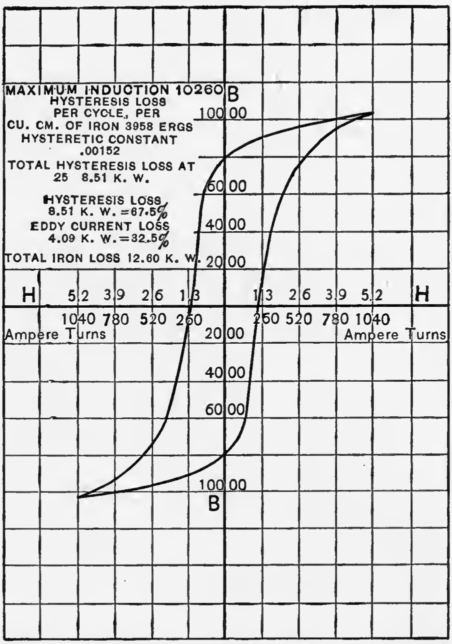


Fig. 113. Hysteresis Curve of a 2,250 K.W. Transformer

Fig. 113, hysteresis curve of a 2,250 kilowatt transformer, shows the curve of hysteresis loss of a 2,250 kilowatt three-phase twenty-five cycle Westinghouse transformer, and Fig. 114 shows the efficiencies at various loads of the same transformer.

The copper loss is determined from the measured resistance, as given by the formula on page 240.

The resistance of the coils is most accurately measured

by the *drop in potential* method, which consists in measuring the volts drop between the terminals of a winding with given currents, from which the resistance is calculated by Ohm's Law. In making this test on large transformers, Peck has modified the drop in potential method to safeguard the measuring instruments against dangerous pressures. When direct current is sent through a transformer winding a magnetic field is induced in the iron; small current vari-

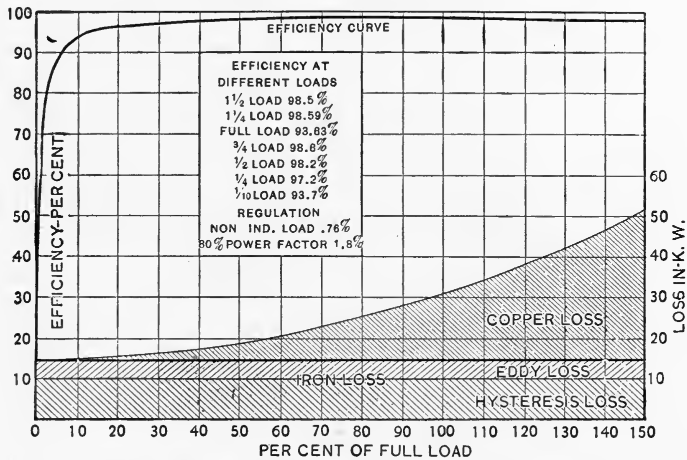


Fig. 114. Efficiency Curve of a 2,250 Kilowatt Transformer

ations will produce variations in the strength of the magnetic field, which may set up sufficiently high E.M.F.'s in the transformer windings to injure the measuring instruments. In Peck's method one winding is short circuited to obviate this danger. When a sudden change occurs in the magnetic field a current is induced in the short-circuited winding, which opposes the change in the strength of the field. In other words, the short-circuited winding acts as

a choke coil to suppress sudden variations in the magnetic field.

But in this method of resistance determination the field does not instantly become stationary, because it is dampened by the short-circuited winding; therefore an appreciable length of time elapses before the field reaches its maximum value.

During the interval in which the field is increasing, an E.M.F. is induced in the transformer winding, which E.M.F. is in a direction to add itself to the E.M.F. due to the resistance; thus the voltmeter reading is slightly higher than it should be on account of the resistance of the winding alone. The correct drop is only ascertained when the field has become stationary.

In making the impedance test the secondary coils of the transformer are first short circuited through an alternating-current ammeter of practically negligible resistance, and a voltage of the rated frequency is impressed upon the primary coils, its value being such as to cause the full-load current to flow. This full-load current can also be measured on the primary side, the secondary being then short circuited. (In this event the small leakage current must be disregarded.) Then the reading of a wattmeter inserted in the primary circuit will almost correspond to the copper loss at full load; while the reading of the voltmeter represents the impedance drop, which is expressed in per cent of the rated primary pressure.

Heating Test. — The average temperature of the coils is determined from the formula

$$t \text{ (rise in degrees } C) = \frac{R_h - R}{0.004\,R},$$

in which R_h = resistance of coils when hot, and R = re-

sistance at room temperature. This is equivalent to dividing the per cent increase in resistance by 0.004. For every 10 degrees above 25° C. the above coefficient should be increased by 1.5 per cent.

Insulation Test.—In making an insulation test, a high-voltage transformer is used, and the rated pressure of the transformer is applied between coils and core. The secondary should be grounded on the core when making a test between primary and secondary of the core. All primary leads should be connected together as well as all secondary leads to insure against undue stresses in any section of the winding.

The requirements of the National Board of Fire Underwriters are: "That the insulation of transformers when heated shall withstand continuously for five minutes a difference of potential of 10,000 volts alternating current between the primary coils and the core, and a no-load run of double voltage for thirty minutes."

Efficiency Tests may be made by any one of several methods, namely, the Ryan Method of Instantaneous Curves, the Mordey Method, and Stray Power Methods.

In the Ryan Method instantaneous contacts are made to obtain the curves of primary and secondary E.M.F., and primary current, the secondary current being measured by an ammeter. From these curves the power in each circuit is calculated, and the ratio between the two gives the efficiency. The principal advantage of this method lies in the fact that both the exact form and phase relations of the waves are sharply brought out.

In the Mordey Method of determining efficiency, the transformer is run at a given load until a constant temperature is reached, as determined by the thermometer or by

resistance tests. Direct current is then passed through the coils, and of such a value that the heating effect keeps the temperature constant. The direct-current power (EI), which is readily measured by a wattmeter, is equal to the aggregate losses with the alternating current.

Stray Power Methods for determining efficiency are quite accurate, and permit of the individual determination

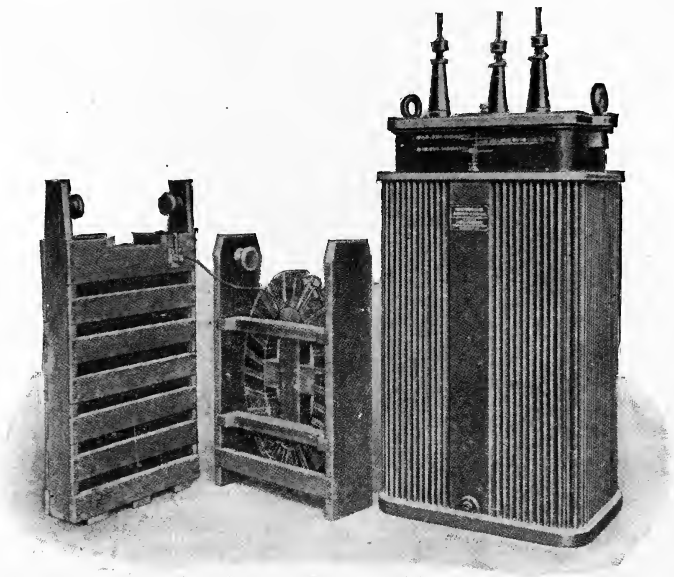


Fig 115. Static Interrupter and Choke Coil

of the losses. The core losses are found from wattmeter measurements in the primary circuit, the secondary being open circuited.

Static Strains in Transformers. — When for some reason it becomes imperative to perform switching operations on the high-tension side of transformers, such as, for in-

stance, the opening of the line under load or short circuit, the charging of a dead transformer from a live line, or a ground on the line, the surges or oscillating currents which follow may produce a rise of potential over double that of the operating potential of the line. This momentary rise of potential will subject the insulation of the primary windings to a severe stress, and may even puncture them, due to a concentration of potential in the layers of windings near the terminals.

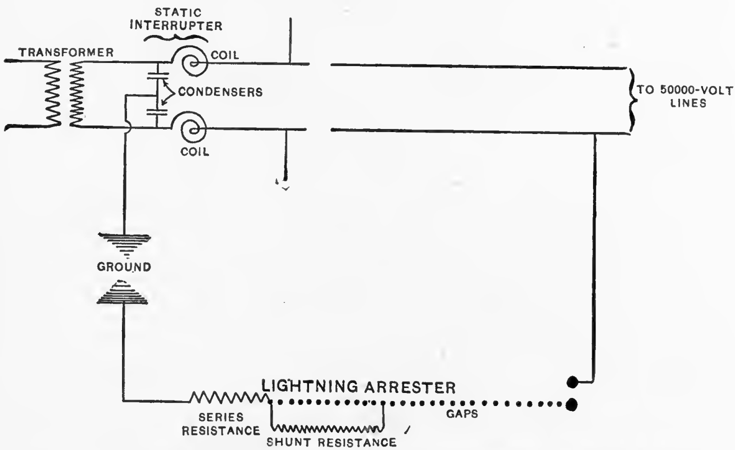


Fig. 116. Diagram of Connections of Static Interrupter and Lightning Arrester

As a protection against the severe static strains to which transformers are subjected a device known as a static interrupter is sometimes employed.

The high-potential leads of transformers in some examples of high-tension practice are passed first through static interrupters, then through fused circuit breakers on one leg, and a plain knife switch on the other leg, connecting thence to three heavy bus wires overhead. Fig. 115 shows a static interrupter in its containing case. Fig. 116 shows

the connection of a static interrupter to protect a transformer from static strains.

Connections of Transformers. — The various possible ways of connecting transformers are: Single phase, two-phase, three-phase star or *Y*, three-phase delta, three-phase *T*, three-phase *V*, two-phase, — three-phase, three-phase star and delta.

Since transmission of electrical power over long distances is practically confined to two-phase and three-phase current, with either one or the other distributing it, only the two- and three-phase connections will here be considered.

Fig. 117 shows a delta-connected primary and secondary.

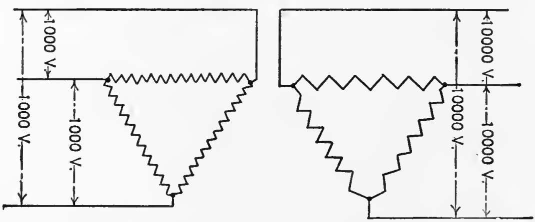


Fig. 117. Three-Phase Delta Connection 1,000 to 10,000 Volts. Maximum Strain to Ground 10,000 Volts

The use of Δ or *Y* connections of transformers is dependent upon the peculiar conditions of operation of the transmission line, the use or non-use of grounded neutrals, and the considerations of economy in translating devices and line construction.

If three-phase transmission is adopted, with three raising transformers connected in *Y* fashion, each of the transformers must be wound for $\frac{1}{\sqrt{3}}$, or approximately 58 per cent of the line voltage and for total line current.

When connected in Δ each transformer must supply the

full-line pressure, and 58 per cent of the current per line wire. Hence the required number of turns in the winding of a *Y*-connected transformer is only 58 per cent of that required by a Δ-connected one, with a cross-section of conductors proportionately greater. The increased number of turns with their additional quantity of insulation, and the extra care that needs to be carried out in the construction of numerous coils and layers, make a much more expensive transformer for Δ connection. The dimensions are also somewhat increased when Δ connection is selected.

In general, *Y* connection possesses the advantage in both size and cost over Δ, when the transformers are of small output at high potential. But *Y* connection necessitates the employment of three transformers, and if an accident happens to one, the others are also put out of service thereby. If Δ connected, the disabled transformer can be cut out and the other two made to furnish three-phase energy up to their maximum output, which is two thirds of the maximum capacity of the three.

When the neutral or common point of junction of *Y*-connected transformers is grounded the potential between coils and core cannot rise above 58 per cent of the line potential, and a possible reduction in insulation between core and coils is feasible. But economy in insulation gained by a grounded neutral is practicable only in the case of small transformers, since with given voltages the space occupied by insulation is relatively larger in a small transformer.

The main advantages offered by Δ and *Y* connections may be thus summed up: (1) The use of *Y*-connected transformers with grounded neutral is more economical, and is generally selected on this score. Without a grounded

neutral its advantage is questionable. (2) If the amount of transmitted energy is large, and the system supplies a large number of widely scattered apparatus, the use of Δ-connected transformers is preferable, since it obviates the danger of possible rises of voltage from various operating causes. With *Y*-connected transformers greater precautions must be adopted, such as, for instance, the use of automatic circuit breakers which will open all legs of the circuits at the same time; else a serious liability of burn-outs on sound transformers will occur when one transformer is disabled.

Many large transmission systems employ *Y*-connected transformers in whole or in part, while others use Δ connections, or a mixed Δ and *Y*, and in most instances with equally satisfactory operation.

Grounding of Transformer Secondaries. — The grounding of the secondary or low-tension circuit of transformers possesses the following advantages:

(1) If one leg of the circuit is properly grounded, the maximum difference of potential between any secondary lead and ground cannot exceed the voltage required by the apparatus in the secondary circuit, because in the event of a breakdown between primary and secondary the current has a path to ground through the grounded secondary lead.

(2) If the secondary circuit is effectively grounded an accidental cross between primary and secondary circuits will result in the blowing of the primary fuse, or fuses of the transformer, and thus serve as a warning to the station attendants of the dangerous conditions of the distributing circuit. Thus, a grounded secondary will protect both life and property.

The disadvantages of a grounded secondary are: (1)

Grounding imposes severe strains upon transformer insulation in case of static disturbances to the line. Such strains are more pronounced during lightning storms and may cause a complete breakdown of the transformer. (2) Aerial lines grounded on poles are liable to dangers from high-tension crosses. (3) Grounded secondaries are liable to cause fires, especially when a service wire is accidentally grounded or becomes crossed with telegraph or telephone wires, which may be blown down by heavy wind storms. The fire hazard from grounded secondaries is, however, greatly minimized if proper precautions be taken to make an effective ground.

The protection to both life and property and other advantageous features gained by grounded secondaries are far more important than the admitted objections; and the best practice in cases where a mixed power and lighting load, or a lighting load only is supplied, is to ground the secondary at its middle or neutral point.

Methods of Installation. — The method of transformer installation adopted is mainly dependent upon the particular operating conditions, the capacity of the plant, and the potential employed in transmission.

American high-tension transformer practice has resolved itself to the following general methods of installation:

(1) In the power house on the main floor, or on the gallery floor, or in separate masonry or concrete cells.

(2) In a separate or transformer house.

(3) In a sub-station — "step-down" transformers.

(4) In the basement of the power house.

Practice in high-tension transmission as regards the proper place for locating raising transformers differs considerably, and in addition to the governing factors already mentioned is influenced in large measure by considerations of economy.

In cases where only moderate outputs of energy are developed, and when it becomes imperative for reasons of economy to utilize every available inch of floor space, the transforming apparatus should be located on the main floor of the generating station, adequate precautions being taken to thoroughly insulate it from the walls and supporting material. The disadvantage of this method lies principally in the element of danger involved in placing high-tension apparatus in close proximity to the moderate tension generating apparatus.

Current practice is now tending towards the installation of the step-up transformers in a building apart from the power house. The transformer house is constructed of either the same or of different material from the central station, and is either an annex of the main building, or is an entirely separate building in close proximity. When transformers are installed in a separate building, the low-pressure leads are usually conducted from the power house to the transformer house in open cable ways — the wires being lead covered. In most instances this cable way is on a level with the top of the switchboard.

Transformers Used in High-Tension Practice. — Two general types of transformers are used in long-distance transmission practice, *viz.*, core type and shell type.

According to the method adopted for keeping the temperature down, transformers are classified as air-cooled, oil-cooled, water-cooled, and water-cooled, oil-insulated transformers.

The selection of one or the other of these types is mainly governed by considerations of economy in operation and of floor space. The air-cooled, or air-blast transformer possesses the advantage of being able to quickly and effec-

tively radiate its heat; and hence all of its coils are kept at a nearly uniform temperature, thus avoiding all danger from charring of insulation and possible burn-outs. The air-cooled type is, however, more expensive to maintain than the oil-cooled kind, except in cases where a bank of transformers is supplied by one blower. The air-blast type is principally used on circuits under ~~three~~ 30 kilovolts. The oil-cooled type is more economical of operation than any of the several kinds, since the oil with which it is filled for insulation purposes keeps the windings from overheating. On the other hand the oil-cooled type does not radiate its heat very rapidly, owing to the poor heat-conducting properties of oil, and hence for a given output it must be of larger dimensions than the air-cooled type.

The water-cooled, oil-insulated type of transformer is coming into extensive use in hydro-electric plants, on account of the easy and effective reduction of temperature which is possible with this form of cooling. The water is kept in constant circulation by means of a pump, the casing of the transformer being provided with a series of pipes running through the coils, or else with a water-jacket between the windings and the outside casing. Since in most instances transformers used in high-tension transmission are of sufficient size to permit of the laying of water-pipes in close proximity to the coils, this becomes a highly efficient method of keeping the temperature down to safe limits.

In plants where the level of the forebay is about six feet below that of the transformers, recourse is sometimes made to a siphon method of maintaining circulation, instead of pumping it through the pipes. In this method of water-cooling, duplicate main intake pipes equipped with strainers are brought through the canal wall below the low-water

level. The transformer coils are bridged between the low-water level and other pipes which lead several feet down to the tail-race. The intake and discharge pipes are connected by a valve, which permits water to flow directly through the discharge-pipe vents, and so creates a vacuum. When this valve is closed water is at once siphoned through the transformers. Thus a constant supply of water can be maintained through the coils, and with no expense other than the initial cost of installing the siphoning apparatus.

A common vacuum gauge is generally used to indicate the condition of the vacuum, the discharge pipe of each transformer being fitted with a small brass pipe about 12 inches long, and $\frac{3}{8}$ inches in diameter at one end and $1\frac{1}{2}$ inches in diameter at the other end. A single mercury **U** tube, connected between the central small diameter pipe and its upper end, affords an accurate indication of the water circulating through the transformer. The quantity of water required to keep the temperature of transformers down to reasonable limits is about 0.4 gallon per minute for a 75 kw. size, about one gallon per minute for a 500 kw. size, and approximately 1.5 gallons per minute for a 1,000 kw. transformer.

All types of artificially cooled transformers are open to the objection that if the blowing or pumping apparatus used to cool them should become disabled the transformers would also be put out of commission, or be liable to burn out from overheating.

(3) Installation of transformers in sub-stations. When the transmission voltage must be reduced to a value suitable for the operation of motors, converters, lights, or other apparatus along the line or at the main distributing point of the circuit, the step-down transformers are usually in-

stalled in sub-stations, located as near as possible to the apparatus to be supplied.

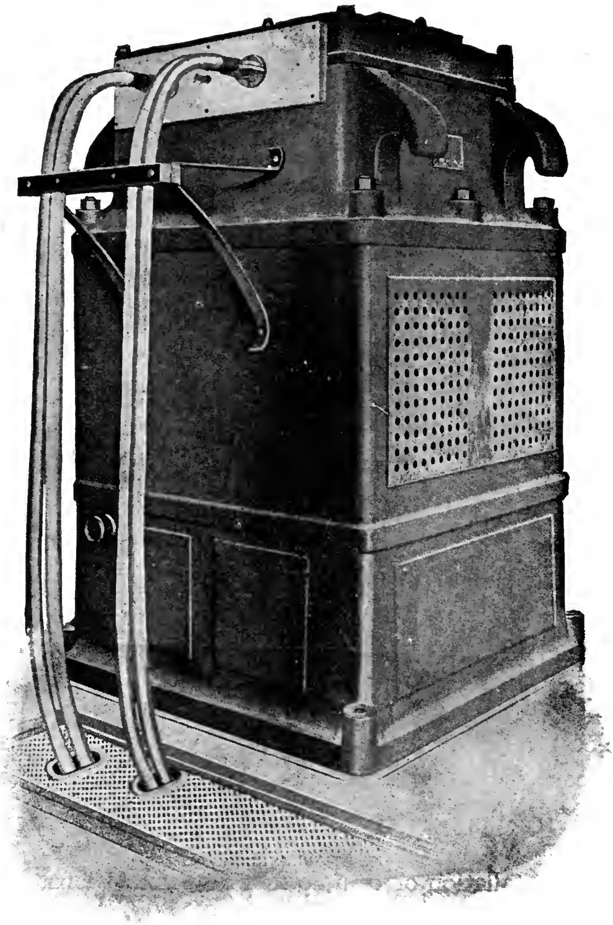


Fig. 113. A 2,750 Kilowatt Air-Blast Transformer

Transformers installed in sub-stations are generally "banked" in parallel, and connected so that when the load

is light only one transformer is connected in circuit, the primaries of the others being open circuited. As the load increases the other transformers are gradually cut in; in

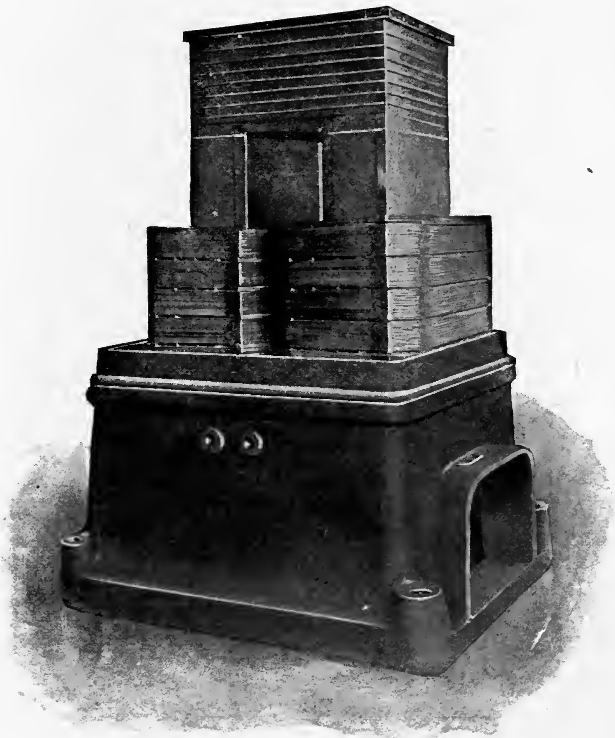


Fig. 119. Construction of Air-Blast Transformer

this way the core losses are kept in fair proportion to the useful energy.

The installation of high-tension transformers in buildings other than those that are intended for electrical apparatus only is now prohibited by the underwriters' rules.

Fig. 118 shows a 2,750 kilowatt Westinghouse air-blast transformer of the shell type, and Fig. 119 illustrates the construction of this transformer, showing the ventilating ducts in the core. The windings of both primary and secondary are divided into a number of flat coils, cotton

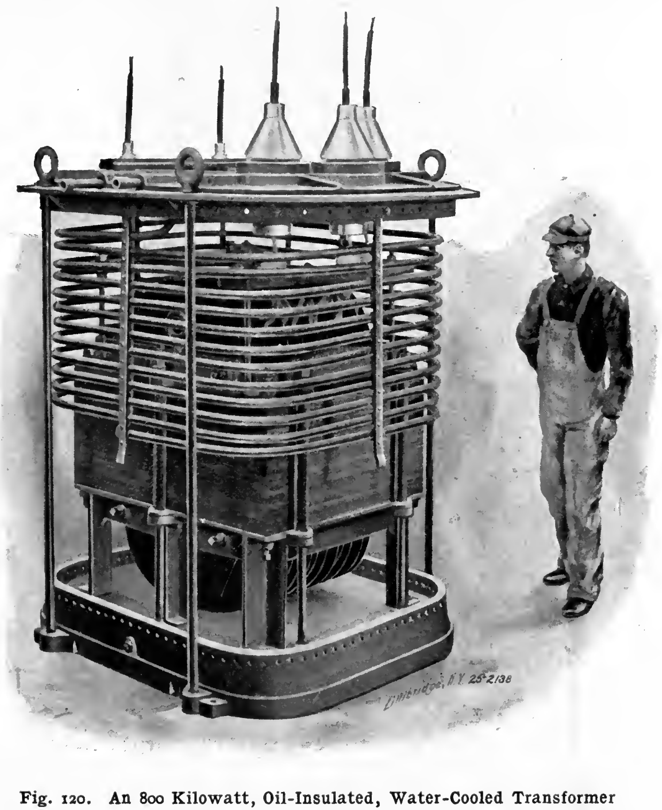


Fig. 120. An 800 Kilowatt, Oil-Insulated, Water-Cooled Transformer

covered. The primary is made up of flat copper strips consisting of one turn per layer. The coils are each separately insulated, and the space between each is filled

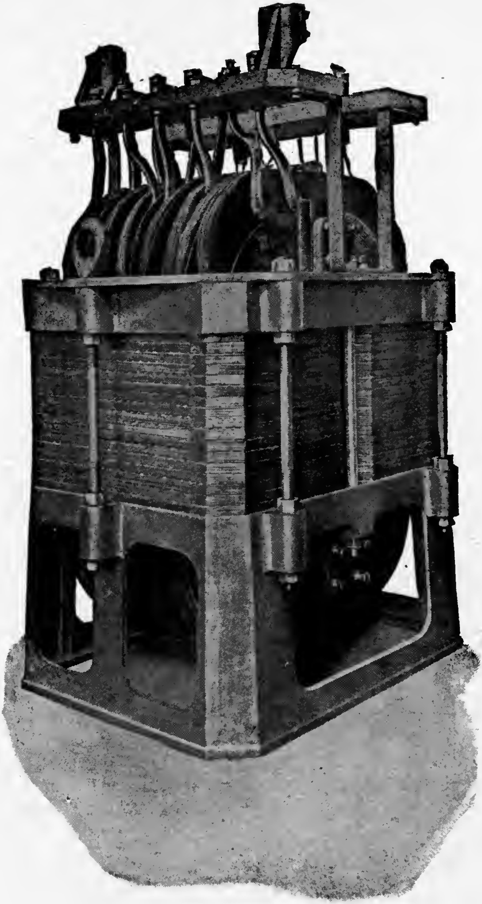


Fig. 121. A 50,000 Volt Water-Cooled Transformer

with heavy insulation. Each layer of coils is separated from the other by a strip of a special, high-resistance insulating material, while the completely assembled coil is incased in a

built-up insulation of high dielectric strength and moisture-proof character. The secondary is wound in a similar manner, of rectangular cross-section copper conductors. In cases where large currents are taken from the secondary, the winding consists of several conductors in parallel.

Fig. 120 shows an 800 kw. Stanley, oil-insulated, water-cooled transformer of the shell type, and illustrates the method of winding employed. The one here shown is wound to give a secondary E.M.F. of 34,675 volts. The primary is divided into sixteen coils and the secondary into eight coils. Each primary coil is made up of 73.5 turns of copper strip, one turn per layer, with three layers in parallel. Two of the primary coils are placed in position with a sheet of micanite between them on the core, and the groups alternate or are sandwiched in between the secondary coils — a secondary between two primaries. The object of this mode of construction is to permit of ample insulation, and also to oblige all of the magnetic flux to interlink with all of the coils.

Fig. 121 shows a 950 kilowatt, 50,000 volt, Westinghouse, oil-insulated, water-cooled transformer, with the casing removed. The method of winding is essentially the same as that of the air-blast type, the spread-coil arrangement being characteristic of both types. The coils are spread apart at the ends outside the core to allow the oil to surround each coil.

BIBLIOGRAPHY

Alternating Current Machines. — Sheldon and Mason. D. Van Nostrand Co. New York. 1903.

The Transformer. — Bedell. MacMillan Co. New York. 1897.

The Alternating Current Transformer. — Baum. McGraw Publishing Co. New York. 1903.

High Tension Transformers. — Farley. Central Station, New York. August, 1903.

The Relative Fire Risk of Oil and Air-Blast Transformers. — Rice. Transactions of American Institute of Electrical Engineers, Vol. 21, p. 5.

Terminals and Bushings for High Pressure Transformers. — Moody. Transactions of American Institute of Electrical Engineers, Vol. 21, p. 15.

Static Strains in High Tension Circuits and the Protection of Apparatus. — Thomas. Transactions of American Institute of Electrical Engineers, Vol. 19, p. 213.

Reactance Drop and Reactance Factor of Transformers. — Kennelly. Electrical World and Engineer, New York, July 20, 1901, p. 92.

LIBRARY OF THE UNIVERSITY OF CALIFORNIA

CHAPTER VIII

MOTORS

SYNCHRONOUS MOTORS

Relation Between Generator and Motor Speed, Torque, and Output.

IF an excited single-phase or polyphase alternator be brought up to normal speed and then connected to an alternating-current circuit of the same periodicity and E M.F. it will run as a motor, and its speed in revolutions per second will equal the quotient of the periodicity by the number of pairs of poles. When operating under these conditions the motor is said to be working in synchronism, or its rotor is revolving at synchronous speed. This synchronous speed is not literally the speed of the generator which is supplying the motor with energy, but is a speed which if multiplied by the number of poles produces a value equal to the alternations of the generator. Thus a motor with half the number of poles as the generator will have double its speed in revolutions per minute, and *vice versa.*

The speed of a synchronous motor is independent of the pressure, and can be varied by varying the speed of the generator. Hence, closeness of regulation of the prime mover supplying synchronous motors is of prime importance, since the armature of the motor possesses a fly-wheel property of sufficient magnitude to consume a relatively large amount of energy without greatly varying its speed.

Moreover, there will be an interchange of currents between the motor and the generator which will cause troublesome regulation, and also diminish the motor output.

The behavior of a synchronous motor on starting is nearly similar to that of the induction motor. Its torque at starting may range from zero to 25 or 35 per cent of the full-load running torque, depending mainly on its design. The torque of the synchronous motor is a function of the terminal E.M.F. and is limited by it chiefly.

The limit to the output of a synchronous motor is the heating of the machine. Polyphase synchronous motors of good design can be made to carry from three to five times full load. With further increase of load they drop out of synchronism, and can only be brought into synchronism again by removal of the load.

Methods of Starting Synchronous Motors. — The starting torque of a synchronous motor being too low to bring it up to speed under load, some extraneous source of power is necessary to perform this task, the auxiliary device being disconnected as soon as synchronism is attained. For this purpose synchronous motors are generally provided with induction motors for starting them, the capacity of the auxiliary being about one-tenth that of the synchronous motor. The small motor is usually geared to the shaft of the main motor, as shown in Fig. 122, which is an illustration of a 500 horse-power motor.

In connecting a synchronous motor to the mains, it is essential that the motor should not only be running at synchronous speed, but also that the phase difference between the motor E.M.F. and the impressed voltage should be 180 degrees. The determination of these points is accomplished by means of a synchronizer.

When synchronous motors are brought up to speed without the aid of an auxiliary device, the method of starting is generally as follows: The field circuit is first opened and the armature connected either directly to the source of supply, or to a starting compensator which reduces the supply E.M.F. The armature windings produce a mag-

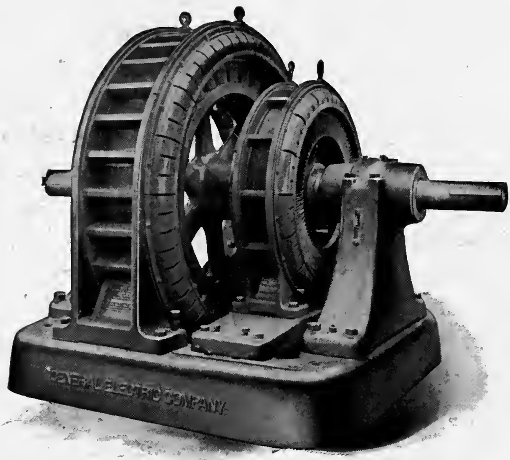


Fig. 122. A Synchronous Motor with Auxiliary Starting Motor

netizing effect which sets up enough flux in the poles to furnish a low starting torque.

The exciter current is then switched on to the field and the motor gradually brought up to synchronism. The starting current is limited only by the impedance of the armature windings, and may have a value ranging from 150 per cent of full-load current to two or three times nor-

mal operating current. The external load is subsequently thrown on the motor through the medium of a friction clutch or equivalent appliances which cause the load to be gradually applied to the motor after it has attained synchronous speed.

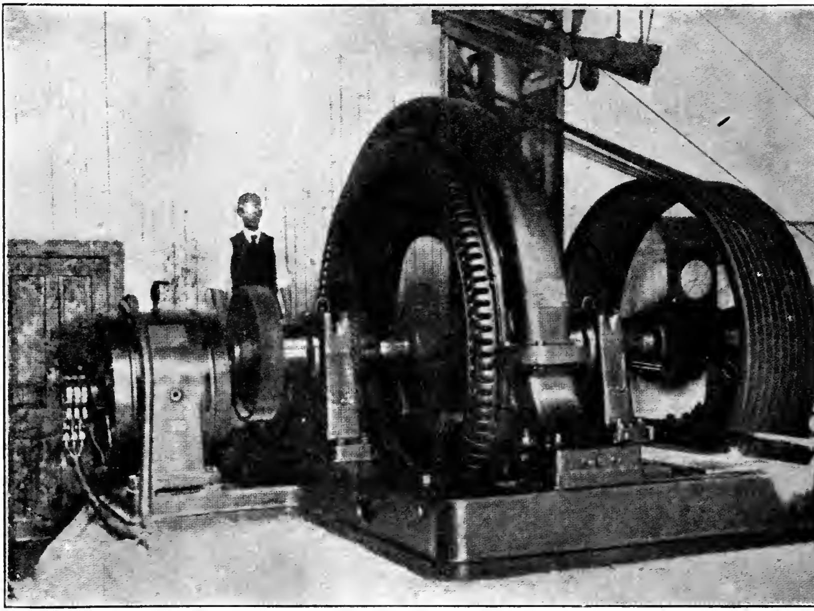


Fig. 123. Synchronous Motor Belted to Shafting

Fig. 123 illustrates a synchronous motor belted to a line of shafting on which is mounted a friction coupling.

The chief objection to starting the load by means of friction clutches lies in the danger of a break-down in the field-coil insulation, due to the high pressure generated in the field by the varying flux. To obviate this each field

coil is provided with a break-up switch to open circuit the coils on starting. The taps or leads from each coil are led to the switch blades, — which are mounted on an easily accessible part of the motor frame. When the motor falls into step with the generator, the switch is closed, which puts the field in series and also throws it in circuit with the exciter.

The Use of Synchronous Motors as Voltage Regulators on Long-Distance Circuits. — On long-distance circuits containing a number of pieces of inductive apparatus in circuit, not only is the power factor of the system apprceiably lowered thereby, but objectionable lagging currents are produced in certain parts of the system. The great flexibility of the synchronous motor is taken advantage of in this class of work to overcome the bad effects caused by apparatus of inductive character. By increasing the excitation of a synchronous motor the power factor can be made equal to unity for any load. Likewise an increase of exciting current will give a proportional increase in pressure produced by the motor, so that by a proper adjustment of the excitation, the E.M.F. generated by the motor can be increased considerably above the voltage impressed upon its terminals. When the operating conditions are exactly opposite, *i.e.*, when the field excitation is low, the E.M.F. generated is lower than the impressed volts.

Under the first set of conditions, the current will be a leading one, while under the second it will lag behind the impressed volts. Over-exciting a synchronous motor will cause it to behave like a big condenser; and so operated it will provide for both energy and wattless components of current up to its rated output in amperes.

The amount of current absorbed by a synchronous motor

depends upon its field excitation, there being one value of exciting current for which the current in the armature is a minimum.

These properties of the synchronous motor make it a valuable piece of apparatus for regulative purposes, outside of its motor functions, since by producing a phase dis-

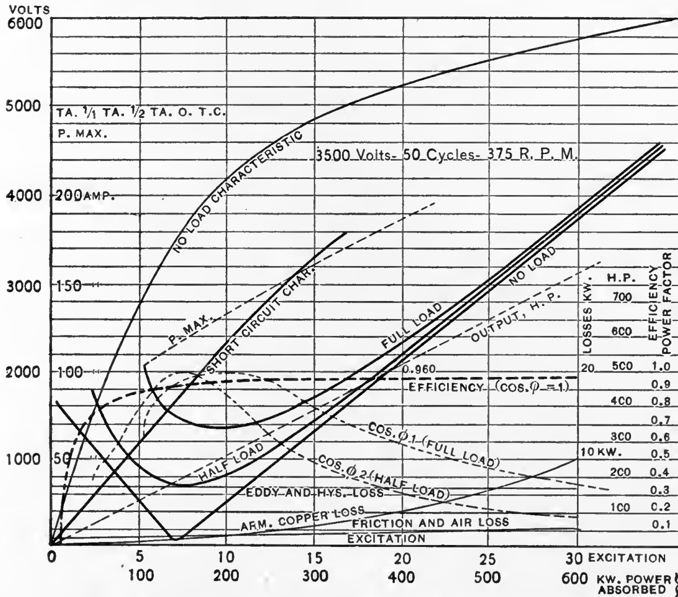


Fig. 124. Curves of 525 H.P. Three-Phase Synchronous Motor

placement between its current and voltage, the reactance caused by the inductance of the line and inductive apparatus can be wholly or partly neutralized. Hence, by properly distributing such motors along a circuit a low power factor caused by induction motors, or apparatus of like nature, can be corrected to any desirable extent.

Another very valuable feature of the synchronous motor

is that in an emergency, such as a failure in the source of current supply, the motor can be made to perform the function of a generator by driving it from some extraneous source of power, and thus become the generator at the sub-stations, supplying energy to induction motors, lamps, or other dead loads in circuit. In many stations this convenient property of the machine is taken advantage of to such an extent that during day hours synchronous motors discharge their normal functions, while at night, or whenever the peak of the load occurs, the motors are operated as generators.

Troubles of Synchronous Motors.—A synchronous motor, both electrically and mechanically, is almost similar to an alternator, and requires the same auxiliary apparatus, such as an exciter and indicating instruments. It is also generally provided with a starting motor or other device. Hence, like the generator, any failure or breakdown of the exciting machine will put the motor out of operation.

If the exciting circuit is suddenly ruptured the high E.M.F. induced by the armature may result in a "field discharge," which is liable to puncture the insulation of the coils.

Being provided with moving contacts — collector rings, commutator, and brushes — the usual troubles from this source, such as destructive sparking and short circuiting, are liable to occur.

On starting up, trouble or injury is liable to result from improper or unsystematic performance of the various operations. Thus, synchronizing may be attempted before the motor is in exact phase, or when it is below normal speed.

Should the load of a synchronous motor (which may possess a large inertia) be thrown on too suddenly, the

motor may not possess a large enough torque and fly-wheel capacity to keep its speed, and will be brought to a standstill.

If the motor is stopped by a failure of the source of current supply, it will not start of its own accord when the current is restored, but requires to be put in operation by the starting motor.

The electrical connection between generator and motor being rigid and unalterable, the operating current of the motor depends upon the steadiness or uniformity of the frequency of the supply current, or in other words, upon the constancy or uniformity of the generator speed and other synchronous motors in circuit.

The motors endeavor to keep exactly in step with the speed of the supplying generator. Any variation of the latter tends to cause a corresponding variation of motor speed. This sets up a pulsation or vibration on both sides of a mean position which may increase to such an extent as to throw all synchronous apparatus in the circuit out of step.

"Pumping" or "hunting" is also liable to occur when the mechanical load on the motor is suddenly changed to a valve which exceeds the limiting torque and the load has considerable inertia.

A synchronous motor is also liable to cause trouble or annoyance by coming to a standstill when the generator quickly speeds up, due to the inability of the motor to increase its speed suddenly without exceeding its maximum torque. In the event of a short circuit in the transmission system, a synchronous motor may turn generator and thus greatly augment the intensity of the short circuit by increasing the line current.

THE INDUCTION MOTOR

An induction motor closely resembles in its performance a direct-current shunt-wound motor, the main points of difference being that the operating current of the direct-current motor is conducted into the armature by means of brushes, while the operating current of the induction motor is an induced current, and that the induction motor has no physical field magnet poles.

The essential elements of the motor are a primary or stator and a secondary or rotor. The primary winding in most cases is connected to the source of current supply, and in addition to carrying the exciting current it performs the office of inducing the working current in the secondary conductors.

Rotation of the secondary member may be regarded as being due to a rapidly varying magnetic field which the revolving member follows. This shifting magnetic field is the resultant of two or more alternating magnetic fields differing in phase.

The rotor of an induction motor may be of the squirrel-cage or short-circuited type, or the variable resistance or polar type.

Rotors of the squirrel-cage type are generally "wound" with copper bars embedded in slots in a laminated steel core. The windings or inductors, which are of low resistance, are all connected in parallel to short-circuited rings placed at each end of the rotor. Since the currents induced in the inductors are obliged to flow parallel with the axis of the motor, the reaction set up by them against the field flux is in a direction to be most efficient in causing rotation.

The short-circuited or squirrel-cage type of motor of small inductance possesses the following features :

(1) Break-down point of high value; (2) moderately large magnetizing current; (3) fairly large current for starting and for starting torque; (4) moderate percentage drop in speed; (5) high power factor; (6) high efficiency at full and overloads.

In induction motors of the variable resistance or polar type the rotor is wound with a definite series of coil windings, which correspond to the polar windings of the stator. The characteristic features of the polar or variable resistance type of induction motor are: (1) Moderate breakdown point; (2) small magnetizing current; (3) low percentage drop in speed; (4) torque proportional to the starting and running current; (5) high power factor; (6) high efficiency at intermediate and full loads.

The squirrel-cage type of motor finds its most useful field of application on power circuits where the conditions of operation call for low starting effort and steady full load. It is also particularly adapted to cases where the motor is required to run overloaded, or on circuits of fluctuating voltage.

The particular sphere of usefulness to which the variable resistance type of motor is adapted is on circuits where close regulation is imperative, such as combined power and lighting service, and under conditions where the motors are usually run underloaded.

Operation of Induction Motors. — Calling the speed at which the magnetic field rotates n_1 and the speed of the rotor n_2, the relative speed between any given inductor on the revolving element and the rotating field will be $n_1 - n_2$. The ratio of this speed to that of the revolving field is called the slip; hence the slip is

$$S = \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1}.$$

The value of the slip is usually given as a certain per cent of the synchronous speed, n_1.

Calling the flux emanating from any given north pole of the primary Φ maxwells, then any single secondary inductor will have an effective E.M.F. induced in it equal to

$$1.11\, p\Phi n_1\, 10^{-8},$$

in which p represents the number of poles.

The E.M.F. so induced has a periodicity which differs from the periodicity of the impressed E.M.F., being s times the frequency of the latter.

If the secondary rotated in synchronism with the primary the secondary frequency would be zero; if the secondary remained stationary the frequency of its current would equal that of the current in the primary.

In commercial conditions of operation the periodicity of the E.M.F. in the secondary winding is of low value, since the slip of most motors is of small value (from 2 to 15 per cent).

In a squirrel-cage secondary the determination of current in a single inductor presents considerable difficulty, since the E.M.F.'s in all the inductors are of different magnitude at any given instant. It is also possible that in some of the windings the current and E.M.F. may be flowing in opposite directions.

When an induction motor is running without load, the speed of the revolving member is very nearly equal to that of the rotating field, being equal to $n_1(1 - s)$. Hence, the E.M.F. generated is only sufficient to set up a current in the secondary windings large enough to make the electrical power equal to the losses in the iron and copper, and those due to windage and friction. A very feeble torque is produced by the magnetic pull of this current.

On applying a mechanical load to the rotor pulley, a drop in speed occurs due to an increase in the slip. With increase of load the speed of the rotor falls further away from synchronism, while the current and E.M.F. therein increase in proportion, and the rotor receives additional increments of energy corresponding to the additions in load. The force exerted by the increased current exerts a torque which is in proportion to the increase of energy — that is, up to a critical point.

Under varying loads the magnetism of the rotating field which cuts the rotor inductors varies also; and with increase of slip an increasing amount of primary flux passes between primary and secondary windings without cutting them. The tendency of the increased secondary currents to set up a cross-magnetizing action causes the increase in magnetic leakage; the effect of which is not only to reduce the torque for an equivalent secondary current, but also requires an increased slip to give the same current.

The curves in Fig. 125 exhibit the relation between torque and slip for different secondary resistances. The solid lines represent torque, and the broken lines, current. As the curves show, the greatest torque which a motor can exert is the same for various secondary resistances. But when giving this maximum torque, the rotor speed differs with the difference of resistance in the rotor. This characteristic of the induction motor is employed to keep down the excessive starting current which follows when a motor is connected to its source of supply.

In Fig. 126 are shown the relations between the torque, speed, power factor, current, and efficiency of a modern induction motor working under average conditions of practice. With an increase of impressed E.M.F., there is a

corresponding increase of magnetic flux interlinked with the secondary, and hence a proportional increase of secondary current.

The torque exerted by a motor is proportional to the product of the magnetic flux and the ampere-turns of the secondary; hence, the torque of an induction motor varies

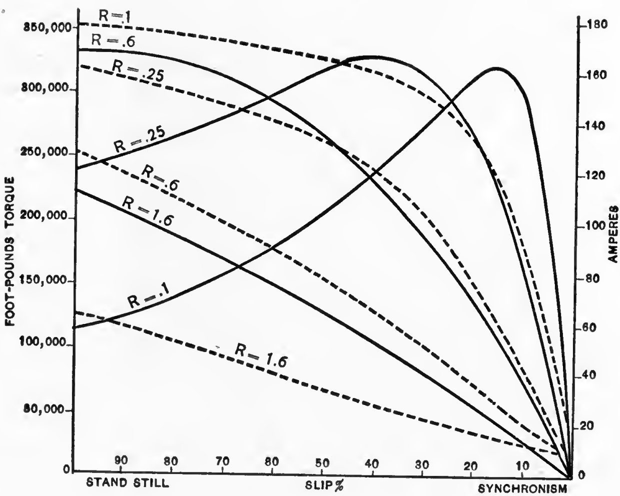


Fig. 125. Relation Between Torque and Slip in Induction Motors

as the square of the impressed voltage. From this it follows that the output of an induction motor varies when it is used on circuits of varying voltages.

Speed Regulation of Induction Motors. — Variations in the speed of an induction motor can be accomplished either by varying the pressure impressed upon the primary, or by varying the resistance in the rotor, or by changing the

number of field-polar planes by commutation of the stator windings.

The first two methods depend upon the principle that the torque of the motor is proportional to the product of stator flux and rotor current; hence for a fixed torque the product is a constant. If the voltage impressed upon the

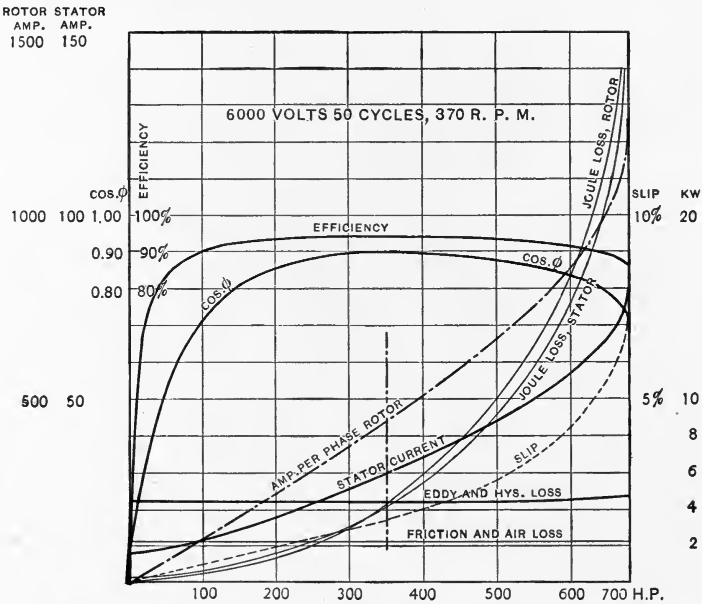


Fig. 126. Relations Between Torque, Speed, Power Factor, Current, and Efficiency

stator is lowered a reduction of stator flux and also of rotor current ensues. Hence, the speed of the motor decreases until sufficient E.M.F. is generated to give rise to a current which, when combined with the diminished flux, will afford the original torque.

The first method of speed control — changing the impressed volts at the motor terminals — requires the use of

a compensator or external reactance, and the motor should possess high constant rotor resistance. The compensator and its controller are generally separate from the motor. The former is fitted with the requisite number of taps from which leads are conducted to the controller. By manipulation of the controller handle, a gradual variation of the impressed voltage is effected, which causes a corresponding variation in the speed.

Speed variation by altering the resistance is effected by inserting resistance in the rotor circuit, the resistance being varied in graduated steps. This method requires the use of an external rheostat or controller with sufficient resistance to dissipate a goodly amount of energy. Fig. 127 is a diagrammatic representation of the connections of the controlling rheostat of a three-phase motor. When the secondary element revolves, collecting rings are necessary to connect the windings electrically with the external resistance. An increase of rotor resistance lessens the rotor current and necessitates a drop in speed to bring its value up to normal, hence the efficiency of operation is lowered by this method.

A reduction in impressed voltage results in a reduction of motor capacity or output, since the output of an induction motor varies as the square of the impressed voltage.

Alteration in the speed of an induction motor by changing the number of polar planes is extremely complicated, and requires a complex switching apparatus in addition to a compensator. The variations of speed are also limited to full, one half, and one quarter speeds. This method is occasionally used under conditions which demand half-speed and half-load torque.

Efficiency and Power Factor of Induction Motors. — Since the losses in an induction motor are of a similar

kind to those in a generator, *i.e.*, core, copper, and friction losses, the efficiency can be considerably increased by the generous use of both iron and copper. Efficiencies of modern induction motors range from 70 to 94 per cent, depending upon their size and the conditions of operation.

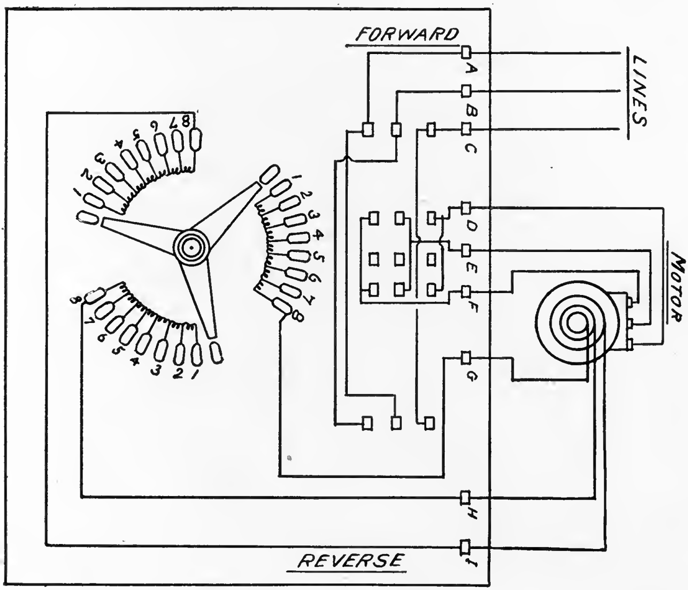


Fig. 127. Connections of Controlling Rheostat of Three-Phase Induction Motor

Motors for factory and shop work are frequently designed to give their maximum efficiency at about three quarters load. This is due to the fact that such motors are only required to give full load at infrequent intervals, the average working conditions calling for about 20 to 30 per cent less load than their rated output.

The power factor of an induction motor is the ratio of

the total current received to the energy current, or the current which supplies its losses and does the work at the shaft. The apparent efficiency of an induction motor is the product of the power factor and the actual efficiency.

The power factor of modern induction motors at full load ranges from 75 to 92.5 per cent, depending upon their capacity and design. Since a low power factor is caused by magnetic leakage, it is feasible to improve the power factor by making the air-gap as short as is consistent with mechanical clearance; also by reducing magnetic density in the iron, which reduces the magnetizing current. But applying these methods and maintaining high efficiency greatly increases the cost of the motor.

Faults of Induction Motors. — The salient objections to the induction motor are:

(1) The starting current at full load (with reasonable efficiency) is several times the full-load current. This fault is characteristic, however, only of the squirrel-cage motor.

(2) The current consumed in giving full-load starting torque may be from four to six times full-load current.

(3) High starting torque with moderate starting current is obtained at the expense of considerable, and not infrequently cumbersome auxiliary apparatus, such as collector rings, brushes, and rheostat.

(4) Low power factor.

(5) Inflexibility of speed control.

Although in many instances the majority of these objections to the induction motor are valid and tenable, in the majority of cases the faults are due either to the adoption of the wrong motor for the conditions desired, or else the use of motors of bad design.

In regard to the first fault, let us consider a comparison between the variable resistance in the secondary induction

motor and the direct-current shunt motor, started by an external rheostat in its armature circuit. There is practically no difference between the two as regards the mode of starting, the purpose of the rheostat in both cases being to prevent the excessive rush of current which always follows when any motor is connected to its supply circuit. It is true, however, that the drop in voltage at the terminals of other apparatus (on account of this large starting current), when an induction motor is started up, is somewhat greater than the drop which follows the connection of a direct-current motor to its source of supply. In many instances such trouble is brought about by a low power factor, or by faulty design.

Regarding the starting torque of the induction motor, it may be said in general that if abnormal means are adopted to secure very high starting torque, the limit will be reached much earlier with the direct-current shunt-wound motor than with the induction motor of the type first considered.

Just as the direct-current motor may be started, stopped, reversed, or run at high, low, or intermediate speeds, by means of a rheostat, and with small torque or large torque, so likewise may the induction motor be operated under identically the same conditions.

This is equally true of an induction motor which is not provided with slip rings, but has its speed controlled by varying the voltage impressed upon it. In certain kinds of power service, it is highly essential that a motor should act as a constant-speed machine when running at any one of a large number of widely varying speeds. In other words, a varying torque should not appreciably affect the speed. Such a requirement cannot be met by any kind of motor under purely rheostatic control, under the cited con-

ditions, since the torque in connection with the resistance entirely determines the speed of operation, an increase of either lowering it, and a decrease of either raising it.

Induction motors of recent manufacture have given a power factor when starting with a given torque of practically the same as when running at that torque; and as the full-load power factor of a well-designed motor of this type may be as high as 90 per cent, the power factor when carrying a load requiring full-load torque may be as high as 90 per cent.

With an induction motor of the squirrel-cage type there is considerable liability of annoying disturbances if the motor is started under load, or run below normal speed, due to the low power factor of this type of motor. At full speed, however, the power factor may be as high as, or higher than, the power factor of an induction motor under rheostatic control.

Although the starting up of squirrel-cage induction motors gives rise to more or less line disturbances, their somewhat higher efficiency, and the fact that circumstances often arise when the motor can be started under light load, render the objectionable feature nugatory.

The efficiency of an induction motor is not entirely dependent upon the power factor of the system, it being quite feasible to design a motor for a low power factor and a high efficiency or *vice versa*. At medium and light loads the efficiency of the induction motor is slightly in excess of that of the direct-current motor. At such loads, however, the current consumption of the induction motor is slightly greater than that of a direct-current motor of equal output. At full load and equivalent currents consumed at full load, the advantage is held by the direct-current machine.

Types of American Induction Motors. — Fig. 128 shows the primary of a 500 horse-power Westinghouse Type C,

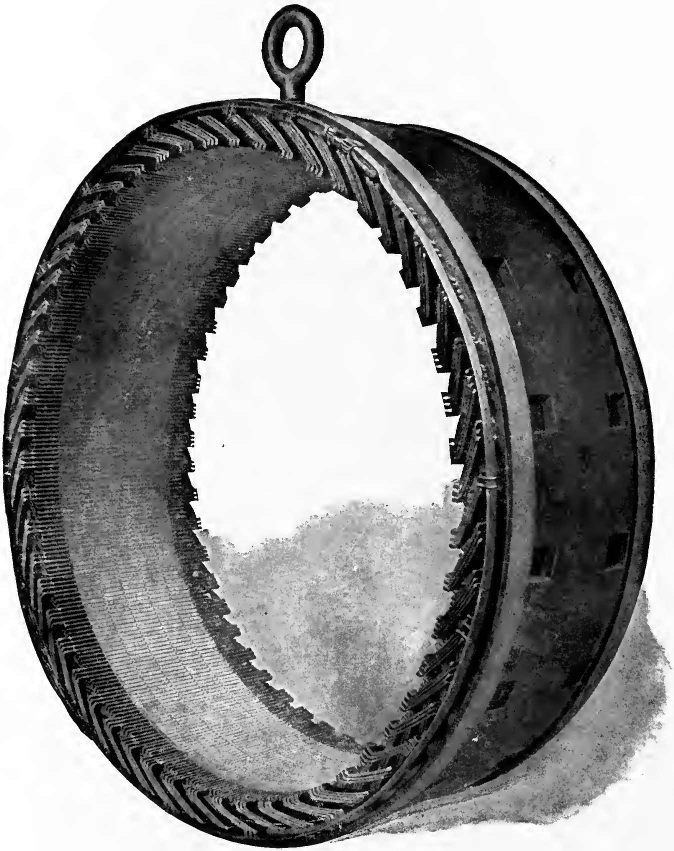


Fig. 128. Stator of a 500 H. P. Induction Motor

squirrel-cage induction motor designed for constant speed. Fig. 129 shows a completely assembled 150 horse-power Westinghouse motor. The frame of the motor is made

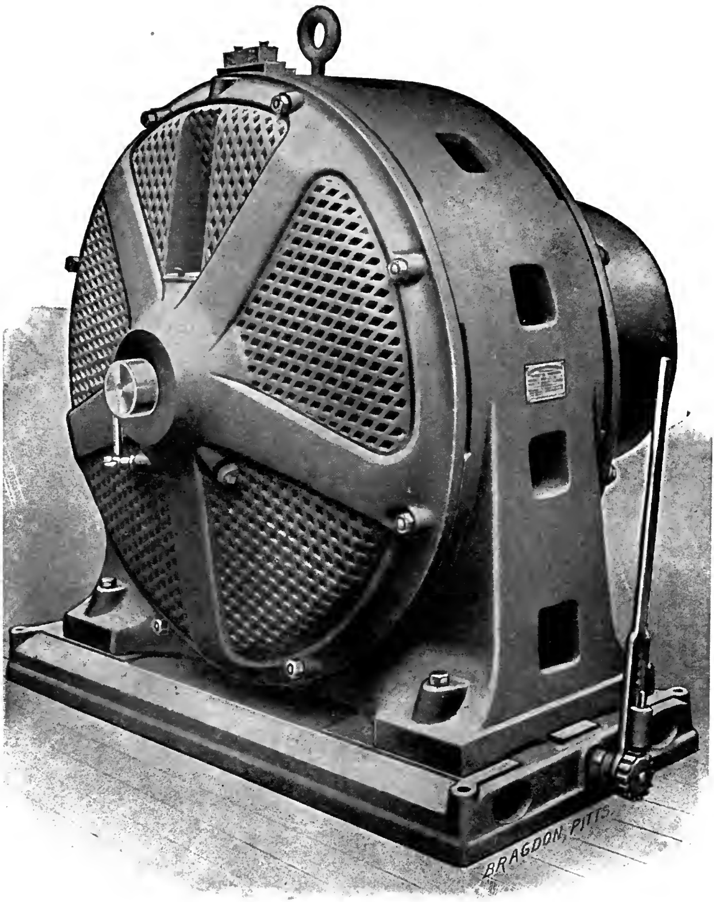


Fig. 129. A 150 H. P. Induction Motor

of cast iron divided in a horizontal plane. The primary is built up of laminated sheet steel and constitutes a hollow cylinder with internal slots in which the winding is laid. The laminated rings of which the cylinder consists are of segmental design and are dovetailed. These segments fit into corresponding slots in a hollow shell made of cast iron, which is rigidly held in the frame of the motor.

The winding consists of copper strap made into coils and bent into the proper form. The terminal blocks through which current is supplied to the motor are located on the side of the frame. The rotor is built up of laminated steel discs, mounted on a spider. The rotor inductors consist of rectangular copper bars embedded in partially closed slots, all conductors being short circuited.

Fig. 130 shows a General Electric squirrel-cage, constant-speed motor of 750 horse-power capacity.

The Repulsion Motor. — The repulsion type of alternating-current motor invented by Professor Elihu Thomson, consists virtually of a direct-current armature revolving in an induction motor field structure. Like an ordinary induction motor there is no electrical connection between primary and secondary. The primary may be wound for a high line potential, while the secondary pressure may be of any value suitable for satisfactory commutation, since it is short circuited on itself through the brushes.

The behavior of the repulsion motor is nearly identical with that of the direct-current series motor, *i.e.*, it shows maximum torque at starting, increase of torque with increase of speed, with nearly constant efficiency throughout wide variations of speed.

Load and impressed voltage limit the maximum speed

of the motor, the maximum speed, however, bearing no relation to the synchronous speed. The motor circuits have a comparatively high reactance, so that the power

Fig. 130. A General Electric 750 H. P. Induction Motor

factor is low on starting; but with the repulsion motor a low power factor is not associated with a small torque, the maximum torque occurring simultaneously with the smallest power factor.

The power factor increases with increase of load, and

attains a fairly large value at one third synchronous speed. Power factors of nearly 90 per cent have been obtained throughout wide variations of speed.

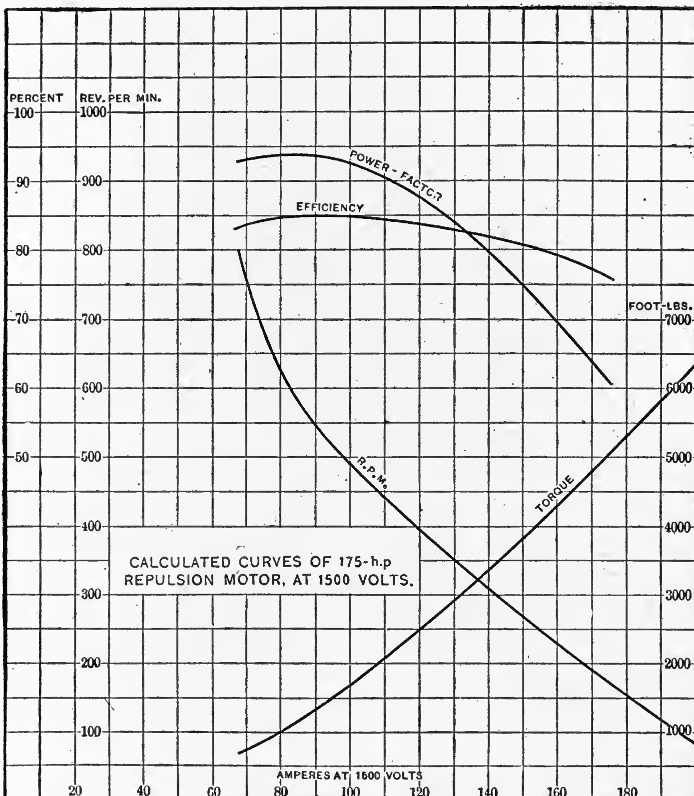


Fig. 131.

The high power of the repulsion motor is due to the leading current, which is generated by the conductors of the secondary cutting the primary flux. This leading cur-

rent is, however, not of sufficient magnitude at practical speeds to entirely compensate for idle currents, but by the addition of an auxiliary or second circuit a compensated type of motor is produced which may be made to give unity power factor at any load.

The efficiency of the repulsion motor ranges from 80 to 85 per cent (including losses in couplings, or gearing), for motors of from 50 to 200 horse-power.

Fig. 131 shows the calculated characteristics of a 175 horse-power single-phase 1,500 volt repulsion motor, presented by Mr. W. I. Slichter in a paper before the American Institute of Electrical Engineers. From these curves it can be readily seen "that the repulsion motor is well suited for efficient operation at light loads, and possesses fairly good constants at low speeds."

BIBLIOGRAPHY

Elements of Electrical Engineering. — Steinmetz. McGraw Publishing Company. New York. 1902.

Alternating Currents and Alternating Current Machinery. — Jackson & Jackson. Macmillan Co. New York. 1901.

The Induction Motor. — De La Tour-Mailloux. McGraw Publishing Company. New York. 1903.

Notes on the Theory of the Synchronous Motor. — Steinmetz. Transactions American Institute Electrical Engineers, Vol. 19, p. 781.

The Repulsion Motor. — Steinmetz. Transactions American Institute Electrical Engineers, Vol. 21, p. 75.

Speed-Torque Characteristics of the Single-Phase Repulsion Motor. — Slichter. Transactions American Institute Electrical Engineers, Vol. 24, p. 6.

CHAPTER IX

CONVERTERS

A CONVERTER is a transforming apparatus consisting of one field winding and one armature, the latter being connected to a direct-current commutator at one end and alternating-current slip rings at the other end.

When the machine is designed to transform alternating into direct current it is termed a synchronous converter. When it is designed to transform direct current into alternating current the machine is termed an inverted converter.

In high-tension electric transmission the converter finds its chief use in transforming alternating into direct current suitable for operating railway motors, factory motors, etc.

If the brushes which rest on the slip rings be supplied with alternating current of the proper pressure, the armature will rotate like the armature of a synchronous motor, that is, in synchronism with the E.M.F. impressed on the circuit. When rotating in this manner, direct current may be taken from the brushes on the commutator.

The power which is delivered to the slip rings of a converter must be sufficient to supply the direct-current circuit, and also overcome the losses due to resistance, inductance, hysteresis, friction, windage and eddy currents.

The armature winding of a converter is of the closed-coil type, and similar to that of a direct-current dynamo, with the taps leading to the slip rings.

Each slip ring is connected to the armature winding by as many taps as there are *pairs* of poles on the field magnet, these taps being equidistant from each other.

A converter may be fitted with any desirable number of rings. When fitted with n rings the taps are distant from each other by $\frac{1}{n}$th of the distance between the centers of two successive north poles from each other.

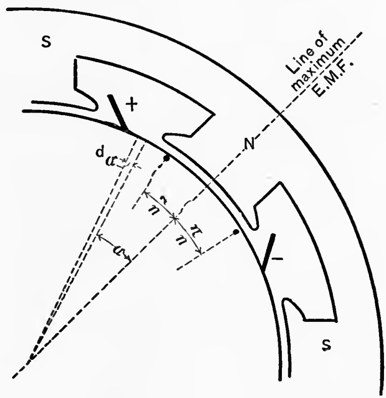


Fig. 132. Section of Periphery of Commutator of Converter

The E.M.F. at the several brushes of a converter may be found in the following manner:

Let E_d = pressure between successive direct-current brushes.

E_n = effective pressure between successive rings of an n-ring converter.

e_m = maximum E.M.F. in volts induced in any given armature conductor. (This E.M.F. is generated when the conductor is under the center of a pole.)

c = the number of armature conductors in a unit angle (electrical) of its periphery.

The electrical angle subtended by the centers of two successive poles of like polarity is equal to 2π. In the diagrammatical representation of a section of the periphery of the commutator, the pressure set up in a given conductor is considered as varying as the cosine of the angle of its position with respect to a point directly under the center of a given pole, the value of the angle being taken in electrical degrees. Thus at a given angle a in the diagram, Fig. 132, the E.M.F. produced in a conductor is $e_m \cos a$ volts.

Consider an elemental section of the armature. In each section there are cda conductors, in each of which is the above E.M.F. If these conductors are connected in series the pressure which is generated is equal to $e_m c \cos a\, da$ volts.

If the E.M.F. between any two successive direct-current brushes be derived by integration and be written equal to this value E_d, the magnitude of e_m can be determined.

Thus,
$$E_d = \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} e_m c \cos a\, da = 2\, e_m c$$
$$\therefore\ e_m c = \frac{E_d}{2}.$$

The electrical angular distance between the taps of two successive rings of an n-ring converter is equal to $\frac{2\pi}{n}$. Hence the maximum E.M.F. is generated in the windings between the two taps when the taps are spaced as equal angular distances from the center of a pole. The value of this E.M.F. is equal to

$$\sqrt{2}\, E_n = \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} e_m c \cos a\, da = 2\, e_m c \sin \frac{\pi}{n}$$
$$= E_d \sin \frac{\pi}{n}.$$

Hence the effective pressure between successive rings is

$$E_n = \frac{E_d}{\sqrt{2}} \sin \frac{\pi}{n}.$$

To ascertain the maximum value of the alternating current supplied to a converter, assume that after deducting the losses therein the power intake in alternating current equals the direct-current output. Disregard the losses for the moment, and let E_n represent the voltage and I_n represent the alternating current in the armature windings between successive slip rings. Then for the sections of the armature periphery covered by each pair of poles,

$$E_d I_d = n E_n I_n$$

where E_d represents the quantity assigned to it above, and I_d is the current between successive direct-current brushes. Hence, the maximum value of the alternating current is

$$\sqrt{2}\, I_n = \frac{2\, I_d}{n \sin \frac{\pi}{n}}.$$

Ratios of Conversion and Capacity. — The effective pressure between the successive rings of a converter is, as has been shown, equal to

$$E_n = \frac{E_d}{\sqrt{2}} \sin \frac{\pi}{n}.$$

If the numerical values representing converters with different numbers of rings be substituted in the equation, it is found that the coefficients by which the pressure between direct-current brushes must be multiplied in order

to ascertain the effective pressure between successive rings is as follows:

For two-ring converters . . .	0.707
For three-ring converters . . .	0.612
For four-ring converters . . .	0.500
For six-ring converters . . .	0.354

Owing to the non-sinusoidal distribution of flux in the air-gap of commercial converters, however, these coefficients are only approximate.

Converters of the synchronous type with closed-coil windings on the armature have the following relative capacities: as a

	Capacity
Direct-current generator . . .	100
Single-phase converter . . .	85
Three-phase converter . . .	134
Four-phase converter . . .	164
Six-phase converter	196
Twelve-phase converter . . .	227

Modern converters can stand overloads which are only limited by satisfactory commutation.

Methods of Starting Converters.—Since the synchronous converter is a synchronous motor it usually requires some device to bring it up to speed. The three most important methods used in practice to start up a converter are: (1) The machine may be directly connected to the supply circuit through auto-transformers or impedance coils. (2) By means of a small induction motor. (3) Starting the converter as a shunt-wound motor from the direct-current end.

(1) If an impedance coil is used it is placed between the line and the armature of the converter, its function being to keep down the pressure and thus obviate the excessive rush of current and consequent line disturbances which would otherwise occur were the rated voltage impressed directly upon the armature when at a standstill. In some instances taps are led out from the windings and the coil is gradually cut out as the armature speeds up, so that when synchronism is attained the coil is completely short circuited. This method of starting may be more or less objectionable, owing to the reaction which follows upon the transmission line. Owing to the fact that the starting current is considerably greater than the full-load running current, and the power factor low, there is but small energy consumption; hence the line disturbances may be undesirable.

If an auto-transformer is used for starting instead of the impedance coil, it is connected in parallel with the line instead of in series with it. A number of taps are led out from various parts of the auto-transformer winding to a central point, so that the impressed voltage on the converter can be regulated as desired. By means of this controller the pressure is gradually raised as the machine comes up to speed. When synchronous speed is attained the rated voltage is impressed on the machine's terminals. Starting a converter through an auto-transformer generally causes less disturbance on the line than the use of an impedance coil. This is due to the fact that the auto-transformer limits the starting current on the line in proportion as the impressed voltage is less than that on the line.

(2) Starting a converter by means of an induction motor. In this method of starting, a small induction motor with a

synchronous speed higher than that of the converter is mounted on one end of the converter's shaft. To start the converter the motor is connected across the secondaries of the transformer. The converter then gradually comes up to speed, after which the induction motor is disconnected and runs normally without load.

(3) Starting the converter as a direct-current shunt motor from the direct-current end is by far the most satisfactory method, as no line disturbances occur. In this case a starting resistance or external rheostat must be provided. The machine is gradually brought up slightly above synchronous speed by cutting out resistance, exactly as a direct-current shunt motor is started. The starting motor is then cut out and its field circuit opened; after which the converter may be connected to the alternating-current mains, the armature quickly falling into synchronism. In cases where several converters are installed in a sub-station, a small motor-generator is sometimes employed to obtain direct current for starting.

The apparent power of a converter at starting is approximately that which is indicated by the volt-ampere input, for converters with either solid or laminated poles. But in a converter with laminated poles the current is more nearly in phase with the E.M.F. on account of the magnetizing current necessary to set up the field flux being smaller because of the subdivided iron. By subdividing the iron the induction can penetrate farther into the poles.

Troubles of Converters.—Hunting of Converters on High-Frequency Circuits. — The converter being a synchronous apparatus is subject to all the troubles of a synchronous motor. But since no mechanical power is taken off, a converter is much more sensitive than a synchronous motor to

slight variations in the supply of electrical energy. The most frequent source of trouble with a converter is a tendency to hunt or pump. This phenomenon, which is both a mechanical and electrical oscillation, is due to a variety of causes: (1) Slight variations in the angular velocity of the prime mover. (2) Slight variations in the voltage impressed on the converter. (3) Absence of sufficient armature reaction. (4) Sudden changes of speed in the prime mover. (5) Sudden change of load.

(1) Variations in the angular velocity of the prime mover are mainly due to faults of design. If the prime mover is a steam engine, the connecting rod may be too short, the governor be over-sensitive, or the flywheel may possess insufficient capacity. An increasing angular velocity results in a slight increase in the frequency of the supply circuit. Hence, the current of the converter increases, and the armature tending to come in a more favorable position with respect to the field, a powerful force is exerted to increase the speed of the converter. But the armature of the converter by reason of its weight possesses considerable inertia, and a certain time interval is necessary to effect a change in its position. Hence there is liability of the synchronizing impulse being oversufficient to bring the armature to the frequency which existed at the time of the impulse, so that the armature will be speeded up above synchronism.

When the converter armature speeds up, the prime mover may be approaching a part of its cycle where the angular velocity, and likewise the frequency of current, are decreasing, so that the tendency is to speed the converter armature above synchronism, and so throw it out of step. The action of the prime mover in the opposite direction, or the other half of its cycle, is the same. Thus the converter is

continually oscillating either above or below its proper phase position, and likewise its instantaneous speed is repeatedly oscillating above or below synchronous speed. Such pumping or hunting action may also cause serious disturbance to other synchronous machinery in circuit.

With water wheels the angular velocity throughout a cycle is constant, and hunting from this cause is of rare occurrence.

(2) Hunting caused by variations of impressed voltage. Changes of impressed voltage may result from over-high line constants, such as inductance or resistance. If a sudden change of mechanical load comes on the converter, a drop in its impressed voltage may occur due to high line inductance or resistance. But since both the magnetic circuit and the armature possess more or less inertia, an instantaneous change to a new condition cannot occur. Before a response to altered conditions can take place, the counter E.M.F. may attain a value high enough to exert a pull on the armature sufficient to alter the phase relations of current and E.M.F. Thus an impulse is given to the converter armature to fall out of step, and hunting ensues.

(3) Hunting caused by absence of armature reaction. Lack of armature reaction in a converter is the result of an equilibrium between two equal and opposite forces. Since the brushes on the commutator are set at the neutral position, the action of the direct current causes a distortion of the field flux in the direction of rotation. The effect of the alternating current (with unity power factor) causes an equal reaction which is opposite in direction. When a change occurs in the values of either or both of

these reactions due to a drop in power factor, the magnetizing or wattless component of alternating currents exerts a demagnetizing action on the field, and thus instable operation of the converter may occur.

The effect of a sudden change of load or speed is to cause a displacement in the phase relations of current and E.M.F. in a manner similar to a synchronous motor. Inertia of the revolving element prevents its instantaneous response to the new conditions. When it does respond the new value is exceeded, and oscillation on both sides of a mean value occurs.

Racing of the armature is a common cause of trouble with inverted converters. If from any cause the current of an inverted converter lags behind its E.M.F., the tendency of the lagging current is to demagnetize the field. The armature then begins to race in a manner similar to an unloaded shunt motor with weakened fields.

Converters operate most successfully on 25 to 40 cycles, although there are a number of Western transmission companies that operate converters on 60 cycle circuits, and with perfect satisfaction. A 60 cycle converter is, however, a very sensitive element on the line, and evinces a decided tendency to hunting. Moreover, a converter designed for use on a 60 cycle circuit must either be run at a very high speed, or else have a large number of poles with brushes set close together. If run at a high speed the brush and commutator wear is quite appreciable, and the humming noise is very objectionable. If the machine is built with a large number of poles the brushes must be set close together to be conveniently handled, and there is danger of flashing or sparking over from one brush to the other on the surface of the commutator.

Types of American Converters. — Fig. 133 shows a 750 kilowatt, six-phase, General Electric converter. The field-magnet yoke is made of cast iron, the upper half being fastened to the lower by bolts located in recesses in the sides of the frame. The object of this method of fastening is to avoid the unsightly appearance of external bolts.

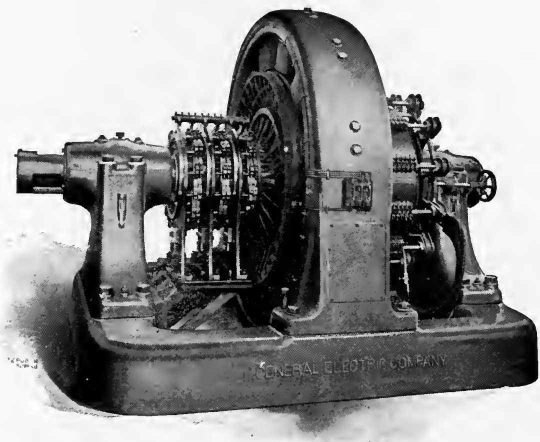


Fig. 133. A 750 Kilowatt Six-Phase Converter

The poles are constructed of solid steel castings and are bolted to the frame to permit of easy removal for repairs. The lower half of the frame is made separate from the bed plate, which permits the entire frame to be slid along the bed plate parallel to the shaft, in case access must be had to the armature.

The armature is bar wound, the upper bars being connected to the lower bars by means of soldered clips on the collector side of the armature.

The collector rings are separated by air spaces to afford sufficient insulation and freedom from short circuits. The brushes on the collector rings are made of copper leaf, while those on the commutator are made of carbon and are held in shank brush holders.

In order to insure cool running, the spokes of the armature spider are fitted with small vanes which produce enough centrifugal action to force an air current between the laminæ of the armature, over its windings and around the poles.

An automatic oscillator or end-play device is used on the shaft to give the armature an occasional to and fro motion parallel to the shaft, and thus give uniform wear on commutator and collectors.

Fig. 134 shows a 1,500 kilowatt, three-phase, Westinghouse converter, which is the largest converter so far constructed.

The armature is wound like an ordinary direct-current generator of large output, the windings being cross-connected so as to facilitate commutation. At regular points around the periphery of the armature, taps are led out to the collector rings on the left side of the armature.

The field of the machine is wound with copper strap in a manner similar to a large direct-current generator, and is compounded to compensate for line losses.

Motor-Generators versus Converters. — The converter as a translating apparatus possesses the advantage of higher efficiency, since there is but one machine instead of two; consequently machine losses are smaller. Likewise its cost is lower, as but one machine is needed.

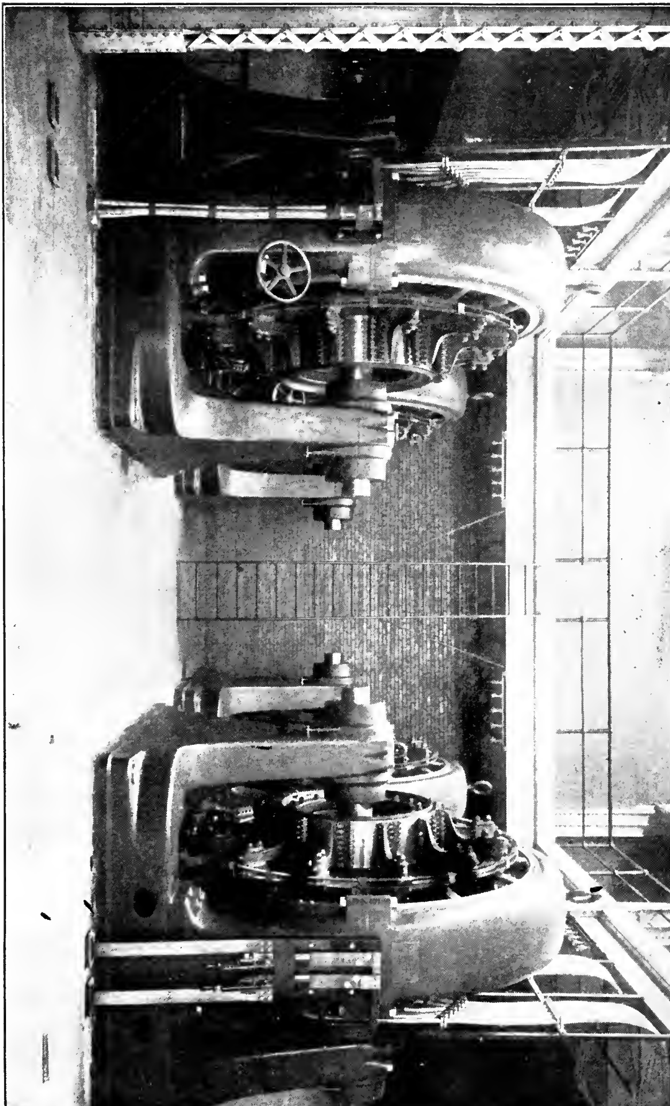


Fig. 134. Westinghouse 1,500 K.W. Converters in a Sub-Station

A converter may be compounded to compensate for the voltage drop which occurs in the generator and transmission circuit; hence it exercises no objectionable influence upon the voltage of the transmission system.

On the other hand, the voltage which is taken off at the direct-current end bears a fixed relation to the pressure of the received E.M.F. However, by maintaining the E.M.F. of supply reasonably constant, it is possible by means of regulating devices or compounding, so to adjust and control the E.M.F. delivered by a converter that the relation between the pressure of supply and delivery will be close enough to be regarded as negligible. Converters are also about 20 per cent cheaper than motor-generators and from 2 to 8 per cent more economical of power.

On low-frequency circuits the operation and behavior of converters are eminently satisfactory, and they require but little attention. But on transmission lines operating at 60 cycles or above, the untrustworthy behavior of converters has led many Western transmission companies to adopt motor-generators as translating devices.

A motor-generator consists of a motor, which may be either of the synchronous or induction type, directly coupled to a direct-current generator.

The salient points of advantage which a motor-generator possesses over a converter are: (1) The E.M.F. of delivery is independent of the E.M.F. of supply and may be adjusted over a wide range to suit any conditions for which direct current may be employed. (2) A motor-generator may be used without putting in a step-down transformer, whereas with a converter the transformer is generally required. (3) If an induction motor is used to drive the generator, periodic fluctuations in the speed of the central station gen-

erator will not affect the satisfactory operation of the machines. In other words, hunting or pumping is unknown when an (induction) motor-generator is used as the translating apparatus. Moreover, momentary interruption of the supplying current or a sudden overload on the induction motor may give rise to little if any disturbance, whereas with a converter serious hunting may occur.

(4) No highly skilled attendants are required when motor-generators are employed.

In American long-distance power transmission practice, the proportion of converters used as translating apparatus is far in excess of motor-generators, which may be considered as indicative of the high state of development which the converter has attained in this country. In Europe the reverse holds true.

Efficiencies of Motor-Generator Sets. — The following table shows the efficiencies of motor-generator sets of various outputs, and at different loads.

Motor-Generator Sets — Combined Efficiency.

	Quarter Load	Half Load	Three Quarter Load	Full Load	One and a Quarter Load	One and a Half Load
400 kw., 375 revolutions . .	70	81	85.5	88.	89.2	90
500 kw., 450 revolutions . .	72	83	87	89.	90	91
800 kw., 450 revolutions . .	73	83.5	87.5	89.5	90.2	91
1200 kw., 450 revolutions . .	77	86	89.5	91.	91.8	92

The figures given apply to Bullock machines. The efficiencies of motor-generator sets of other representative manufacturers will not differ appreciably from these figures.

The following tables are a comparison between the relative efficiencies of static transformers and converters as against motor-generators. The figures apply to 200 kilowatt units in operation at a sub-station of the Buffalo (N. Y.) Edison Company.

	Transformer	Converter	Motor	Generator	Combined Efficiency
Full load	97.5	93.0	95	92	87.4
Three quarter load . . .	97.1	92.5	94	91	85.54
One half load	96.0	90.0	92	88.5	81.42

Comparison between the Net Efficiencies of 200 Kilowatt Units.

	Motor-Generator	Transformers and Converters	Difference
Full load	87.40	89.47	2.47
Three quarter load	85.54	88.70	3.16
One half load	81.42	84.90	3.48

Frequency Converters. — A frequency converter is an apparatus for changing an alternating current of one frequency into an alternating-current of another frequency, which may be either higher or lower than the received frequency. Its principal use is to transform low frequencies into higher ones.

A frequency converter is essentially an induction motor, and operates on the principle of the variation, with slip, of the frequency of its rotor E.M.F.

The usual method for raising the frequency of supply is to couple a synchronous motor to the shaft of an induction

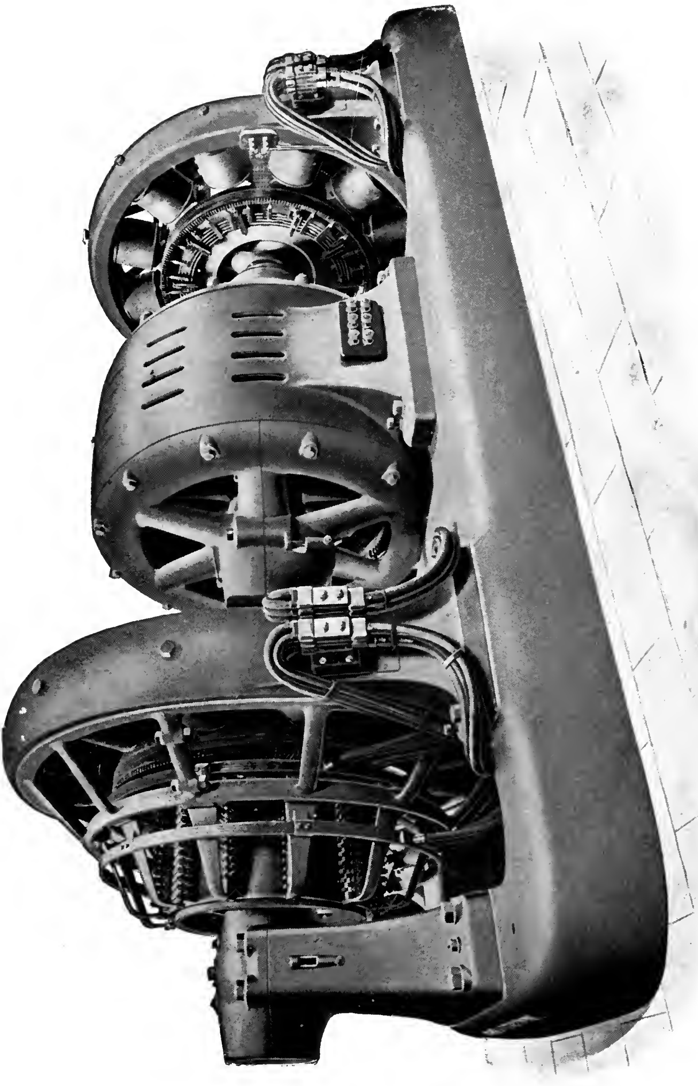


Fig. 135. A Motor-Generator Set — A 1200 H.P. Induction Motor Direct Connected to Two 400 K.W. Generators

motor, and cause the driving motor to turn the rotor of the induction motor in an opposite direction to the direction of rotation of the driven motor's field. The primary windings of the induction motor and also the terminals of the driving motor are connected to the low-frequency source of supply. The higher-frequency current is taken from the secondary

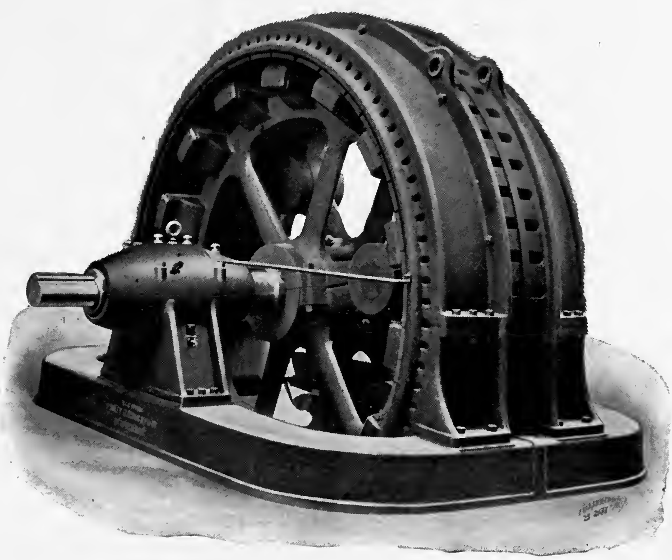


Fig. 136. A Large-Frequency Converter Unit 1

of the induction motor by means of slip rings mounted on the shaft.

The voltage of the delivered current and its frequency are governed by the speed of the rotor. For definite values, they are the algebraic sum of the current variations in both machines. When the rotor is revolved at its rated speed in a direction opposite to its normal direction of rota-

tion, the frequency of the delivered current is double that of the received current. Likewise, if the rotor is revolved at half speed in its normal direction, the frequency of the output is one half that of the supply. The output of the synchronous motor which drives the frequency converter must be of the same proportion of the total output as the increase in frequency is to the higher frequency.

Use of Frequency Converters in High-Tension Practice. — In addition to transforming low-frequency current into frequencies suitable for the operation of lights and other apparatus which require high frequencies for satisfactory operation, or *vice versa,* frequency converters find a valuable field of service in cases where several transmission lines operated at different frequencies supply a center of distribution. In such cases, the frequency converter is an alternating-current generator driven by an induction or synchronous motor.

A notable instance of this kind is that of the electrical supply of Montreal, Canada. Energy is supplied by three transmission companies, all operating at different frequencies. The three frequencies, 66, 60, and 30 cycles respectively, are transformed by five frequency converter units into 63 cycle current which is supplied to all customers in the city. Fig. 136 shows a type of large-frequency converter unit.

BIBLIOGRAPHY

Elements of Electrical Engineering. — Steinmetz. McGraw Publishing Co. N. Y. 1902.

Alternating Currents and Alternating Current Machinery. — Jackson & Jackson. Macmillan Co. N. Y. 1901.

The Rotary Converter. — Berg. Transactions American Institute of Electrical Engineers, Vol. 18, p. 607.

The Design and Action of the Rotary Converter. — Rushmore. (Serial.) Engineering Magazine, N. Y., Vol. 22 (1901), pp. 414–422, 538–552.

Energy Transformations in the Synchronous Converter. — Franklin. Transactions American Institute Electrical Engineers, Vol. 20, p. 876.

Operation of Converters. — American Electrician, N. Y., Sept., 1903.

Voltage Regulation of Rotary Converters. — Lincoln. Electric Club Journal, Pittsburg, March, 1904, p. 55.

CHAPTER X

PRACTICAL PLANTS

Architectural Designs of Buildings for Hydro-Electric Central Stations. — The majority of power houses generating current for long-distance transmission are similar in architectural features, differing chiefly in dimensions, minor details, and materials of construction. The type of building which has now become almost the standard design as a containing structure for hydro-electric machinery is a square or rectangular building with its greatest dimension longitudinally.

Foundations for power houses are usually concrete and granite masonry. In a few instances wooden piles have been used where the character of the soil did not permit the use of a masonry foundation. The foundation of the Sault Ste. Marie structure, which is the largest building thus far erected for housing hydro-electric machinery, has a wooden pile support.

Various materials of construction are employed for power-house structures, among which may be included nearly all of the common building materials, such as wood, brick, concrete, granite masonry, sandstone, corrugated iron, and structural steel. Except for power houses of small output, wood is now rarely used entirely as a building material.

The three materials most employed for this purpose are concrete, brick, and granite masonry, with or without

structural steel frames. Some buildings on the Pacific coast are constructed of corrugated iron over a wooden frame, while in a few instances (notably the Sault Ste. Marie Plant) power houses have been constructed of the sandstone which was excavated from the canal.

Floors for hydro-electric stations are made of concrete, cement, brick, tile over concrete, and, in a few instances, wood. When the structure is provided with a gallery, it is constructed either of wood (rarely) or of steel and concrete; not infrequently it is constructed of a combination of the three materials.

Roof trusses are usually of the arched type and are generally made of structural steel in a variety of designs.

Roof coverings consist of corrugated iron, a combination of concrete tar and gravel, or asbestos covered by one of the numerous patented roof coverings.

The general practice with most transmission companies is to erect as substantial and fire proof structures as possible, since the ultimate economy and safety are far greater.

Arrangement of Machinery and Apparatus in High-Tension Central Stations. — In the arrangement and location of hydraulic and electrical machinery and auxiliary apparatus in high-tension plants the controlling factors are considerations of safety, space economy, and accessibility, and in many instances the necessity of conforming strictly with the peculiar circumstances of the case.

In most Western practice, where the water supply is conducted through the power plant latitudinally, the hydraulic machines are installed with their shafts parallel to the walls of the structure, or lengthwise in the building and close to the wall. In cases where the water is conducted through the structure longitudinally the hydraulic

machines are usually set with shafts parallel to the width of the building.

When vertical turbines are used the hydraulic units are usually installed in a straight line a few feet from the lengthwise wall of the building.

In some hydro-electric power houses, notably those in the East, the building is divided into compartments by partitions, the turbines being installed in a separate wheel room, and the generators in so-called generator chambers. The wheel chambers generally have arched concrete roofs with concrete floors and sides, while the head wall that separates each chamber from the generator room is 5 or 6 feet thick, and is fitted with a large bulkhead of cast iron, which carries a water-tight bearing for the wheel shaft.

In the location of transformers practice varies widely. They are either installed in the power plant proper on the main floor near the walls, or in line with the space back of the low-tension switchboard on one side and the exciters on the other, or are placed in a compartment partitioned off from the rest of the structure, or are located on the upper or gallery floor. In some plants they are placed in a separate transformer house. In plants where air-blast transformers are used they are placed on the main floor with air chambers underneath or in a basement.

Switchboards in hydro-electric plants are installed either on the same floor as the generators, on the side of the power house or at the end, or are mounted on a platform or rostrum of masonry a few feet above the floor level, or they are installed in a gallery above the main floor. The atter practice is more general in cases of plants of large output at very high potentials.

As in the case of transformers, no uniformity of practice

obtains in the location of switchboards. In many instances, the matter of convenience, accessibility, and economy demands that the switchboard be installed on the same floor as the generators, so that the men attending wheels and generators can also perform the switching operations.

In some high-tension plants on the Pacific coast, the high-potential board is installed separately from the generator switchboards, being usually mounted in a gallery over and slightly to the rear of the generator board, and is placed half way between the inner rail of the crane and the wall of the building, and facing the tailrace.

The lightning arresters for high-tension stations are installed either in a separate building, termed the lightning arrester house, or are located in the main building. Arresters for protecting transformers are mounted on the faces of vertical marble panels located near the transformers.

Parallel Operation of Plants. — Many Western long-distance transmission plants miles apart are successfully operated in parallel, the problem of parallel running being regarded as no more serious than the parallel operation of direct-current plants. A notable instance is the system of the Edison Electric Company of California, which consists of seven plants separated by wide distances, all of which are operated in parallel with the greatest of ease.

Regulation of Plants. — In long-distance power plants one of the highest essentials of successful operation is good regulation. The requirements of close regulation are in the main a recapitulation of the principles outlined in previous chapters. They are: (1) A considerable voltage variation in the generators, and generators and transformers designed for close inductive load regulation; (2) a transmission line so designed that the capacity current will be

a minimum; (3) avoidance of attempts to balance the capacity of the circuits against the power lag; (4) constant capacity of the line balanced with reactance; (5) the variable inductance of circuits and the induction motor load to be balanced by variable capacity in the form of synchronous motors.

Sub-Stations: Materials of Construction and Arrangement of Apparatus. — Architecturally the majority of high-tension sub-stations are closely similar to the main power structures. The type of building generally used is of square or rectangular shape, one or two stories in height, depending on the capacity in translating apparatus which is needed at the particular point of distribution. In Western practice sub-stations are sometimes designed so that a second story may be added to provide for increased demands for power.

Considerations of safety and reliability of operation demand that sub-stations be of the most substantial and fireproof character. Formerly it was the practice to place the translating apparatus in a hastily put up structure, oftentimes of a character which barely protected the machinery from the elements. In the best modern practice as much attention is given to the sub-stations as to the central station, and their construction is of a very rugged character. Brick is mostly employed for constructing sub-stations, although stations of granite masonry, concrete masonry, and sandstone are frequently met with in Western practice.

The incoming high-tension wires are passed into sub-stations through long porcelain sleeves or through marble and glass bushings; and the current is usually conducted through a set of single-throw fused switches, one switch per leg. Thence the high-tension current is passed through

non-arcing lightning arresters fitted sometimes with static interrupters, finally being conducted to the step-down transformers.

Step-down transformers in sub-stations are usually arranged in pairs or groups and installed near the lengthwise wall of the building; or, in case they are the only translating apparatus in the station, are placed near the center of the structure.

Switchboards in sub-stations are generally installed near the lengthwise wall of the structure. In most cases they contain a separate panel for each transformer and are equipped with the necessary measuring and indicating instruments and the protective devices which have been mentioned before (Chapter IV).

The switchboard in most sub-stations is equipped with a high-tension plug board which permits of any desirable combination of the incoming and outgoing circuits. Thus in some cases all of the load may be put on either transmission line, or it may be divided so that the steady load is on one circuit and the fluctuating load on the other; or both circuits may be connected in multiple.

Cost of Electrical Power Transmission. — To justify an electrical transmission project, the value of the energy at the point of distribution should at least equal the value of the generating plant plus the cost of transmission. The cost of energy at the generating end being known and its value at the receiving end, the difference between the two represents the maximum cost at which the transmission will pay.

The factors which enter into the cost of a power transmission scheme are: (1) Cost of water rights, the land flooded by back-water or for a reservoir site; (2) cost of

dam and its auxiliaries which may be conveniently termed the "hydraulic end"; (3) cost of power house and auxiliary structures; (4) cost of station machinery and auxiliary apparatus; (5) cost of transmission lines and translating apparatus; (6) cost of operation; (7) cost of repairs, maintenance, and depreciation.

In most instances there is the additional cost of the water-conveying system, a pipe, flume, or canal line. The cost of hydraulic pipe differs widely. The table on page 60 may be taken as a good average of the cost per foot of riveted sheet steel pipe.

The cost of buildings will include the cost of the main power plant and auxiliary houses, such as lightning arrester and transformer buildings (if such apparatus is not installed in the central station). Also the cost of various sub-stations for distributing the power. Many considerations govern the cost of the generating station, as, for instance, the difficulties of preparing a suitable foundation, the prevalence or absence nearby of the particular building material desired, the cost of transporting the materials of construction to the site, and the cost of labor in the section. The cost of buildings involves too many variable factors to attempt here to give any hard and fast rules.

The cost of machinery includes the cost of turbines or water wheels and auxiliary apparatus pertaining thereto, such as governors, valves, and gate-controlling devices, the cost of generators and station apparatus. The cost of water wheels varies from $2.50 to $7.50 per horse-power output, depending upon their capacity.

In general, the cost per kilowatt of generated power varies from $100 to $250 [redacted].

The Sault Ste. Marie plant complete cost $4,000,000, or

$135 per kilowatt. This is but a moderate cost per unit of power compared with some water-power plants.

The cost per unit of power has many variables, such as the output of the plant, the conditions of operation, the cost of building material in the neighborhood, the cost of labor, and the kind of machinery used.

The cost of transformers varies directly with the highest rate of transmission, and is approximately independent of voltage, the distance of transmission, and the line loss. The cost of transformers varies from $6 to $10 per horse-power. For large capacities a good average figure is $7.50.

The cost of the transmission line proper, which consists of the pole line and the conductors, varies according to the conditions of each case. In the total cost of delivered power the highest and the average rates of power transmitted, the maximum pressure of transmission, the percentage of line loss, and the distance of transmission, fix the ratio of line cost.

The pole line varies in first cost with the distance of transmission, but is almost unaffected by the factors above stated. Since reliability of operation is the foremost consideration in long-distance power transmission, a pole line of the stoutest and most substantial construction is required. In regions where timber is procurable at a moderate cost, the cost of pole lines, exclusive of the right of way, will range from $450 to $600 per mile; a good average is $525. In many instances the right of way will cost nothing.

For a fixed and maximum percentage of line loss, the cost of conductors varies directly with the square of the distance of transmission, and with the rate of transmitted power. The first cost of conductors, however, decreases

with increase of pressure, as the square of the voltage of transmission ; and also decreases with increase of line loss. Hence, the transmission voltage and the permissible line loss at maximum load will fix the weight and cost of line conductors.

With a given amount of power to be transmitted, the length of transmission and the voltage, the weight of conductors required varies inversely as the percentage of energy lost as heat in the wires. A fair average for line conductors is from 18.5 to 20.5 cents per pound for copper conductors, and about 28.5 to 31 cents per pound for aluminum conductors.

The cost of operation, which includes management, labor, and incidental expenses, repairs, maintenance, interest, and depreciation, will vary widely with the circumstances in each case. No fixed and definite figures obtain, since in each transmission plant the cost of operation is governed by different factors. In general, the cost of management, labor, and incidentals ranges from three to eight per cent yearly on the total first cost, depending on the size of the power development and the length of the transmission system ; and hence the number of employees required to operate it.

The cost of repairs, maintenance, interest, and depreciation will also vary with the size and length of the transmission system, the character of the machinery employed, and the line construction. The annual allowance necessary for repairs, maintenance, and depreciation will vary from five to twenty per cent of the total first cost of the transmission. Interest charges will range from three to six per cent per annum on the total investment.

Mr. Alton D. Adams says: "If a given amount of

power is to be transmitted at a certain percentage of loss in the line, and at a fixed voltage over distances of 50, 100, and 200 miles, respectively, the following conclusions obtain: The capacity of the transformers being fixed by the rate of transmission will be the same for either distance, and their cost is therefore constant. Transformer losses, interest, depreciation, and repairs are also constant. The cost of pole lines, depending on their length, will be twice as great at 100 miles, and four times as great at 200 as at 50 miles. Interest, depreciation, and repairs will also go up with the length of the pole lines.

"Line conductors will cost four times as much for the 100 mile as the 50 mile transmission, because their weight will be four times as great, and the annual interest and depreciation will go up at the same rate. For the transmission of 200 miles the cost of line conductors and their weight will be sixteen times as great as the cost at 50 miles.

"It follows that interest, depreciation, and maintenance will be increased sixteen times with the 200 mile transmission over what they were at 50 miles if voltage and line loss are constant."

The cost of an electric horse-power hour at the switchboard in a hydro-electric station will differ in each particular case, on account of the different outlays required in hydraulic installations per unit of developed power. Where only moderate amounts of power are developed the cost per electric horse-power hour at the switchboard may range from 8 down to 1 cent. Where large outputs of power are developed the cost may range from 3 to 6 cents per electric horse-power hour. To obtain the total cost of transmission per electric horse-power, the percentage found by dividing the cost of operation by the number of horse-power hours

per annum of output, must be added to the product obtained by multiplying the cost of a unit of power at the switchboard into the cost of a percentage of a horse-power hour which is lost in transmission.

The sum obtained by adding the cost of a unit of power at the switchboard, the cost of energy transmitted, and the cost of the percentage of a horse-power hour lost in transmission, gives the total cost of transmission per electric horse-power.

The Limitations of Electric Power Transmission. — Theoretically, it is possible to transmit electric power around the globe, provided the available voltage is unlimited. Such a statement follows from the law that a certain amount of power may be conducted to any distance with a steady efficiency and a predetermined weight of conductors, provided the pressure of transmission is increased in direct proportion to the distance.

In practical working, however, the maximum voltage at which it is safe and economical to transmit power is the limiting factor in the present stage of long-distance power transmission. The limits to the pressure which can be employed in practice may be divided into several factors which enter into the transmission part of the system, *per se:* (1) Definite limits to the pressure of transmission beyond which temporary arcing between the wires on a pole will occur, and the less significant but constant exchange of energy from one conductor to another; (2) leakage losses through the air from wire to wire of the line (see Chapter VI); (3) the necessity of stringing cach wire of a transmission line on a separate pole line, or at wider distances apart, thereby greatly increasing the cost of line construction when pressures much higher than those used in present practice are

employed; (4) the difficulty of obtaining an insulator which is capable of withstanding very high pressure.

The first limitation to high-tension power transmission-arcing, is caused by one of several causes. A broken or defective insulator may give rise to a current flow along a wet cross-arm from one conductor to another, so that in time the wood is carbonized, and finally a vicious arc burns up the cross-arm and not infrequently the pole itself.

Lines running in close proximity to the sea coast sometimes have a heavy deposit of salt formed on the insulators and cross-arms which sets up an arc between the conductors, frequently resulting in the destruction of the cross-arm.

The same trouble may occur in cases where the line crosses an alkali desert or runs near a dried-up salt lake or basin. Arcing troubles, however, are less frequent in localities where the lines are not exposed to sea fogs or salt dust.

(2) Leakage losses through the air from wire to wire of a line directly through the air is the most serious limitation to the voltages which can be employed with existing line construction. The most notable experimental work which has been thus far done to ascertain the rates at which energy is lost by passing through the air from wire to wire of the same circuit is that of Messrs. Scott and Mershon at Telluride, Colorado. Lately Professor Ryan, of Leland Stanford University (see Chapter VI), has made a noteworthy contribution on the same subject.

Measurements made by Scott show that the leakage through the air varies directly with the length of the line, as might be presumed. With ~~four~~ 40 kilovolts line pressure and with wires 15 inches apart, the loss between wires was approximately 150 watts per mile. With the same pressure

SEE E

and with conductors 52 inches apart, the loss was only 84 watts per mile. When the voltage was increased to 44,000 and the wires separated by 15 inches, the leakage loss was increased to nearly 413 watts per mile.

At 44,000 volts and a distance of 52 inches between conductors, the loss was only 94 watts per mile. The maximum pressure employed for the conductors 15 inches apart was 47,300 volts, at which the leakage between the two wires became nearly 1,215 watts per mile. At five kilovolts and a distance of 52 inches between wires the loss was 140 watts per mile. As the pressures increased the losses went up at a very rapid rate, becoming at the highest voltage measured (59,300 volts) nearly 1,368 watts per mile.

It is manifest, if the leakage losses increase at a corresponding rate above ~~six~~ 60 kilovolts, which is to be expected, that at above ~~eight and a half~~ 85 kilovolts, the loss will become (with wires 52 inches apart) more than 7,000 watts per mile. If such is the case, it is clear that a long line at this pressure would be impossible. But to overcome this limitation requires only that the electrical resistance of the air be increased by stringing the wires of the circuit at greater distances apart. At the present time the greatest distance apart of the conductors of a transmission line is 78 inches, the three wires of a single circuit being strung on one pole line. There is no reason why this distance cannot be considerably increased if the conditions demand.

(3) Increased difficulties and expense of line construction when pressures above ~~seven~~ 70 kilovolts are employed. From what has been said concerning line leakage it is clear that if pressures above ~~seven~~ 70 or ~~eight~~ 80 kilovolts are employed, the present general practice of stringing wires will have to

be radically modified. In present practice, the two or three conductors of a transmission line are carried on a single pole line, or in a number of instances, several circuits are carried on the same pole line.

Although the method of stringing each wire on a single pole line could be carried up to a limit of perhaps eleven feet between any single wire of a circuit, the cost of the large poles demanded would increase the expense of line construction enormously. Moreover, at pressures of about 90 ~~nine~~ or 100 ~~ten~~ kilovolts this mode of line construction would not reduce the leakage losses to a permissible value.

It is not improbable that when line pressures a few tens of kilovolts higher than present practice come into use, each conductor of a circuit will be carried on a separate pole line. Since the distance between wires with such radical line construction could be made of any desirable value the losses by leakage through the air would be negligible regardless of the voltage of transmission. It would seem that the use of steel towers for carrying the conductors offers the best solution to this limitation.

(4) The difficulties of obtaining an insulator which will not break down under the severe stresses of high potentials impose another limitation upon the pressure permissible in power transmission. Although at the present time insulators have been developed which will safely and satisfactorily withstand pressures of over 150 ~~fifteen~~ kilovolts in laboratory tests, it remains to be seen what will be their behavior when called upon to insulate a transmission line under the trying conditions of actual practice.

The principal shortcoming of high-potential insulators is their relatively low surface resistance as compared with the body of the insulator, which results in insidious break-

downs due to arcs between the insulator pin and the cross-arm.

As the voltage of transmissions has gone up, the length of insulator pins has been gradually increased, so that in some transmissions of the present day a distance of nine or ten inches between the lower wet edge of the insulator and cross-arm has been attained. It is feasible by using still longer pins and umbrella-type insulators of a larger size to increase this striking distance to at least two feet, at which distance breakdowns from this cause would be nearly unknown.

Some experimental work has been done to discover a dielectric which will fulfill the exacting requirements of line insulation to a higher degree than porcelain, although at the present time it seems unlikely that the desideratum will be found. At the least, the insulator problem is a less serious limitation to high-pressure transmission than leakage losses from bare conductors.

BIBLIOGRAPHY

Evolution in High Voltage Transmission. — Scott. Electrical Review, N. Y., Jan. 10, 1903.

Costs of and Losses in Electric Power Transmission. —Adams. Mines and Mining, N. Y., Feb., 1903.

Does Transmission Pay? — Journal of Electricity, Power, and Gas, San Francisco, Feb., 1903, p. 136.

Depreciation of Plants. — Electrical World and Engineer, N. Y., Nov. 17, 1900.

Organization of the Operative Forces of a Transmission Plant. — Hancock. Journal of Electricity, Power, and Gas, San Francisco, August, 1903, p. 277.

Regulation of a Transmission System for any Load and Power Factor. — Baum. Electrical World and Engineer, May 18, 1901, p. 822.

CHAPTER XI

DISTINCTIVE FEATURES OF PROMINENT LONG-DISTANCE ELECTRIC POWER TRANSMISSIONS.

THE SNOQUALMIE FALLS PLANT.

THIS is a 20,000 horse-power transmission from the falls of the Snoqualmie River to Seattle, Washington, about 25 miles distant, and Tacoma, 44 miles distant. The falls have a vertical drop of 270 feet, which is greater by over 100 feet than the falls of Niagara. The water-shed supplying the river is over 500 square miles in area, and contains numerous mountain lakes and natural basins, which it is possible to utilize when the present power development is increased to meet future demands. The river does not freeze during the winter months, and hence the plant is free from the serious difficulties encountered in many other plants, from anchor or floating ice.

The most distinctive feature of the power development is the location of the plant in a subterranean chamber. The reason for this lies in the fact that the great volume of spray at the base of the falls would have kept the building and apparatus damp during the summer season, while in winter the coating of ice on the building would have been a serious disadvantage.

The water is conducted directly into an intake constructed of steel and concrete, and extending about 60 feet along the river bed. To prevent floating timber and driftwood from entering the intake the front is guarded by a grating

of 12 inch by 12 inch timbers placed horizontally with 12 inch spaces between them; the whole is supported by an iron girder frame made into the masonry.

The subterranean power house is located about 300 feet above the falls, at which point a shaft 10 feet by 27 feet was sunk in the bed of the river to the water level below the falls. From the face of the ledge below the falls to the bottom of the shaft, a tunnel 650 feet long and 12 feet by 24 feet in cross-section was excavated. This tunnel extends under the bottom of the subterranean chamber and forms the tailrace. The power house is a chamber dug into the rock formation and is 350 feet long, 40 feet wide, and 30 feet high. Ventilation of the chamber is accomplished by the natural draft through the tailrace.

The mean temperature of the chamber is 55° F. which is very favorable to high generator efficiency.

The main wheel units in the plant are probably the largest and most powerful of the tangential type which have ever been operated under the same head. The original installation consisted of four 2,000 horse-power units. The wheels are of the type (Doble tangential) described in Chapter III.

The water-distributing receiver is 48 inches inside diameter and 20 feet 8 inches in length, and is constructed of marine steel plates $\frac{1}{2}$ inch thick with dished heads. The shell is constructed of two plates 10 feet wide and sufficiently long to make a cylinder with only one longitudinal seam, which is double riveted. All flanges are of semi-steel. The distributing receiver stands directly over the foundation and is held in position by six regulating nozzles, which are mounted in a vertical plane upon the foundation. Thus the water is delivered from the receiver into the

nozzles without undergoing any change in direction. The nozzles are curved so as to direct the water upward against the wheels. Each nozzle is fitted with two tips, the diameter of the jet discharged from each being $3\frac{7}{8}$ inches.

The auxiliary wheels for driving the exciters are also of the tangential ellipsoidal type. They are mounted in steel housings and are supplied with water through a regulating nozzle which gives a jet of 3 inches diameter. The regulating nozzles are so constructed that by merely opening the nozzle to the maximum diameter any trash or foreign matter which may have lodged in the nozzle is immediately washed out, and the nozzle can be adjusted to the proper jet diameter.

There are seven generators in the plant, four of which generate three-phase current at 1,000 volts and 60 cycles. The other three machines are each of 3,000 kilowatts output and generate three-phase current at 1,100 volts and 60 cycles.

The E.M.F. is raised to 30,000 volts by oil-insulated, water-cooled transformers, delta connected on both the primary and secondary sides. Nine of these transformers are of 1,000 kilowatts capacity and weigh 11,000 pounds each; and each requires 500 gallons of oil.

The switchboard consists of fourteen panels of white marble with separate generating and multiplying panels.

The poles for the transmission line are of cedar, stripped of the bark, and either tarred or burnt at the butts. Their average length is 36 feet, but this varies with the contour of the country; the maximum length being 154 feet. Where the lines cross the channel in the harbor, the poles are 154 feet long, 47 inches in diameter at the

butt, and 23 inches at the top, and weigh 2,500 pounds each.

The line is in duplicate and is carried through a right of way averaging 50 feet in width. In some sections of timber land the company has a right of way extending 300 feet on each side of the line, through which sections trees of over 300 feet in height had sometimes to be felled in order to insure immunity from injury to the line.

Two circuits are strung on each pole line, one on each side, with a triangular spacing of 30 inches between conductors. Cross-arms are $4\frac{1}{2}$ inches by 6 inches and 8 and 10 feet long. On all turns and crossings double cross-arms are used. Four conductors are strung on the lower cross-arm, the inner two of which are 75 inches from the center of the pole and the outer two 25 inches from these. The upper cross-arm is 25.5 inches above the lower arm, and on it are strung two wires, each 40 inches from the pole center.

The conductors are of stranded aluminum, and about 125 tons of metal were required for constructing one of the lines. Triple-petticoat porcelain insulators are used throughout. Each insulator is 4.5 inches in height and 6.5 inches in diameter and weighs four pounds. The insulator pins are of locust wood boiled in paraffine. The distance from the lower edge of the insulator to the cross-arm is four inches.

The length of span on the circuit to Seattle ranges from 90 to 150 feet, the average being 110 feet. The sag between spans is about 15 inches, which is much greater than is permissible with copper conductors.

Transpositions divide the line into six equal sections; the spans in which the transpositions are made are hung

between two poles 6 feet apart. Where transpositions are made the circuits are given a third of a turn always in the same direction.

A telephone line of No. 10 B. & S. gauge aluminum wire is carried on the same pole line with one of the power circuits, at a distance of about 5 feet below the power wires. At every fifth pole the telephone circuit is transposed.

In common with most Western long-distance power transmission systems the lines are patrolled, each patrolman having a ten-mile stretch to inspect and report its condition to the sub-stations from booths located every three miles.

The power is utilized in coal-mining operations along the route of the transmission line, and in lighting several small towns. The greater part of the energy is supplied to the cities of Seattle and Tacoma, where it is consumed by manufacturing and street railway properties, etc.

The Missouri River Power Company.—This transmission plant enjoys the distinction of being the first to employ a potential of 50,000 volts and at the present time is transmitting power at 57,000 volts. Current is also generated at 12,000 volts for supplying a small distribution area.

The power plant is located on the Missouri River near Canyon Ferry (Mont.) and is 17 miles from Helena and 65 miles from Butte. A dam 900 feet long was constructed across the river at a point where the walls of a canyon rise to a considerable height. The main dam is built up of earth with a core wall of masonry, located on the east side of the river. The auxiliary dam is a rock-filled, timber crib structure with masonry abutments. The east abutment is about 325 feet from the east bank; and between the abutment is a free spillway 472.75 feet in length. From

the west abutment, a masonry bulkhead extends 90 feet to an almost vertical cliff.

The dam forms a reservoir of about 7 miles length and over 6 square miles area.

The main power house is 228 feet in length and 50 feet in width, and is constructed of granite masonry with steel roof trusses and corrugated iron. It contains a gallery 18 feet wide which extends throughout the building on the west side, and has floors of steel and concrete construction. The masonry used throughout the work was obtained from the region and cut near the site.

It contains a gallery 18 feet wide, which extends throughout the building on the west side, and has floors of steel and concrete construction.

Water for operating the turbines is conducted to the power house through a canal 275 feet long and 54 feet wide. The canal wall is constructed of thick granite masonry and is lined throughout with Portland cement. The head gates are electrically operated by a very ingenious mechanism, consisting of a car moving over rails laid over the east wall of the canal, and equipped with the controlling mechanism ; the clutches are lever operated and the car is equipped with a ten horse-power direct-current motor, receiving current from an overhead wire through the medium of a trolley wheel. The car rails are so designed that they support the car only when it is traveling between gates, or when it is throwing pinions into or out of mesh with the racks on the gate-lifting bars.

The hydraulic equipment of the plant consists of ten pairs of McCormick turbines, two single turbines, and one pair of small units for driving the exciters. Each shaft of the main turbines has two water bearings, one of which is

at the outside of the turbine on the canal side, and the other inside the draft chest. Another thrust bearing of the ring-oiling type is placed outside of the wheel case, close to the generator coupling, and has two solid projecting rings, fitting into grooves in the surface of the bearing. All of the turbines are controlled by Lombard governors. The machines discharge their water into central cast-iron draft chests, and thence through elliptical draft tubes into the tailrace.

The generator equipment consists of ten revolving armature, 750 kilowatt, three-phase, 550 volt, 60 cycle machines, each direct connected to a pair of turbines by means of flexible couplings. Exciting current is supplied by four 150 volt direct-current generators, one of which is coupled to an induction motor, and the other three directly connected to 24 inch turbines.

The switchboards and the raising transformers for the 12,000 volt service are installed on the gallery floor. There is a separate panel for each generator, and each machine is wired directly to its panel on the board.

For the 57,000 volt service there are six raising transformers, each of 950 kilowatts capacity and of the oil-insulated, water-cooled type, cooled by water from the canal.

They are installed in a transformer room between the wall of the power house and the east wall of the canal, and are arranged in two groups with delta connection. The protective apparatus for the 57,000 volt transformers consists of lightning arresters combined with static interrupters. Each lightning arrester consists of 114 units with six small gaps, and a large adjustable gap close to the line.

High-tension switches between the two 57,000 volt circuits are designed so that both groups of transformers

may be put into joint operation on one or both lines; or one group of transformers may be used to operate both circuits.

The 57,000 volt main conductors in the station are 800,000 circular mill cable with rubber insulation and external lead sheath. The line conductors for the 57,000 volt circuit are bare copper cables, each composed of seven strands. The circuit is strung in the form of an equilateral triangle with conductors 78 inches apart, two wires being carried on the cross-arm and the third at the top of the pole. The insulator pins are of white oak, kiln dried and boiled in paraffine. For insulation of the circuits dependence is placed entirely upon the insulators, sleeves, and pins.

Transpositions on each of the main circuits are made at average distances of thirteen miles, making five transpositions to Butte, and giving two complete turns between the power plant and the Butte sub-station.

A telephone line is carried on pony glass insulators, 5½ feet below the power circuit cross-arm, and is transposed every fifteen poles.

The main circuits are carried over a right of way 200 feet wide for the greater portion of the distance, and all trees and brush for a distance of 50 feet on either side of the line are cleared away.

The 12,000 volt transmission carrying 4,000 horse-power is mainly utilized by smelting works at Helena seventeen miles distant. The remainder of the medium tension transmission supplies the incandescent and arc lighting, street railway and manufacturing properties of Helena.

The 57,000 volt transmission to Butte, aggregating about 8,000 horse-power, is consumed principally by the large

Anaconda mine. Power is also supplied to various manufacturing interests.

The Bay Counties Power Company of California. — This transmission system is the longest in existence and was first put in operation on April 27, 1901. The company supplies power from three plants operated in parallel. Power is transmitted at 40,000 volts to Oakland, a distance of 142 miles from the main generating station; and power is supplied to the Standard Electric Company, for transmission to various points along San Francisco Bay, the farthest of which is Stockton, 218 miles distant from the main power plant.

The main power plant of the system is located at Colgate, on the north Yuba River. At a point about eight miles above the power house a dam was constructed across the river. Thence the water is conducted through a flume to a point about 700 feet above the power-house structure. The flume system is laid on a gradient of 13 feet to the mile and has a nominal capacity of 20,000 miner's inches. The flume is about 7 feet wide and $5\frac{3}{4}$ feet deep and is supported on trestles averaging $8\frac{3}{4}$ feet in height. At the point where the flume system ends, five pipe lines conduct the water down the mountain side to the distributing receiver in the power house.

The five pipe lines are each 30 inches in diameter, made of cast iron at the bottom and steel at the top, and anchored in massive concrete blocks. At the foot of the pipe lines is a massive penstock or water receiver, which distributes the water to the water wheels under a head of 702 feet.

The power-house structure is located at the base of the mountain and is 275 feet long and 40 feet wide. It is con-

structed of native rock with steel roof trusses and corrugated iron covering.

There are at the present writing seven hydraulic units installed, consisting of three 3,000 horse-power Risdon wheels, and four 1,500 horse-power wheels, all of the tangential type. In addition to the main water wheels there are two 50 horse-power wheels for driving the exciters. All units are direct connected, and the shafts of the larger units (and the larger generators) have a flange at each end for leather link driving. This arrangement permits any generator to be driven by either of two water-wheels, with the exception of the outer generator and water wheel units. The smaller units are independent of one another, and each is coupled to its respective wheel through flexible couplings.

The generating equipment of the power house consists of three 2,200 kilowatt, three-phase, 60 cycle Stanley inductor alternators, each direct connected to a 3,000 horse-power wheel; and four 1,125 kilowatt generators, each driven by a 1,500 horse-power wheel.

The raising transformers are of the oil-insulated, water-cooled type, and are installed in the main power house.

The transmission line for the 142 mile circuit is in duplicate and is carried on cedar poles with fir cross-arms. The average length of span is 132 feet. The insulator pins are mainly of eucalyptus wood, although on some parts of the system locust is used. The insulators are of porcelain and the special design of Mr. R. H. Sterling, superintendent of the Bay division. The upper part is of porcelain with a very wide lip, and cemented on to a glass insulator with a long petticoat by means of a sulphur cement.

One of the transmission circuits is composed of three No. 00 hard-drawn copper wires, strung in the form of an

equilateral triangle with 36 inches space between wires. Line joints on the copper circuits are of the regular Western Union type with nine wraps on each side and soldered the entire length. The other circuit, which is strung parallel to the copper line, is composed of three No. 0000, seven-strand aluminum cables with joints of the thimble form. Both circuits are transposed every mile by making one third of a turn.

The Hudson River Water Power Company. — The power house is 392 feet long and 71 feet wide with a space 28 feet by 34 feet omitted at one corner. Extending across the entire width of the structure and 40 feet in the direction of its length is a compartment, in which are installed the transformers and the high and low-tension switchboards. The remainder of the structure is divided into two sections in the lengthwise direction by a water-tight brick wall which gives the wheel chamber a width of 34 feet and the generator chamber a width of 35 feet. Ten steel penstocks each 12 feet in diameter enter from the canal along the outside wall of the canal. The water supply from eight of these penstocks drives a pair of horizontal turbine wheels that discharge through a single draft tube, and are coupled direct to a 2,500 kilowatt generator. The other two penstocks supply each one pair of wheels direct connected to a 2,000 kilowatt generator and also a wheel coupled to a 200 kilowatt exciter dynamo.

The power house has a basement in that part in which are installed the transformers and switchboards, with the dam as one of its side walls. The basement contains a central air chamber wherein are installed blowers which maintain a pressure of five eighths ounce per square inch for cooling the transformers on the floor above.

The low and high-tension switchboards are installed at opposite sides of this air chamber. The switching on the high-tension board is performed by motor-operated oil switches, the legs of which are contained in separate brick compartments. The 30,000 volt connections are fastened on the stone and concrete masonry by means of porcelain insulators. For this purpose each insulator is fastened to an iron pin and has a cast-iron top or cap. The point between the pin and the insulator and also the point between the insulator and the iron cap are made with a thin mortar of Portland cement.

The step-up transformer equipment is entirely of the air-blast type, and each unit is designed to operate at 2,000 volts primary and either 15,000 or 30,000 volts secondary. The transformers are connected in groups of three to a generator unit.

Lightning arresters for protecting the transformers are installed in stone and brick cells, each unit in a separate cell. Each conductor of the transmission circuit is connected to an arrester plate through a knife switch.

The transmission line is carried on chestnut poles of a standard length of 35 feet and regularly spaced 100 feet apart. On curves and turns the pole tops are pulled over 6 to 12 inches by guy wires made of seven-strand No. 12 B.W.G. galvanized steel wire having a maximum tensile strength of 80,000 pounds. On some angles pole braces not under 22 inches in circumference at their tops are employed.

The standard cross-arms used are 10½ feet long, 4 inches thick, and 6 inches deep. Each arm is given two coats of metallic paint. Each cross-arm is fastened to the pole by a single through bolt ⅞ inches in diameter and galvanized.

The bolt has a thread cut over 4 inches of its length and is used with its nut next to the cross-arm with galvanized washers under both head and nut. Each cross-arm is braced with a single piece of galvanized iron bent into bow form.

The insulator pins are of iron. Two types are employed, one for the straight runs and the other for curves and corners. The pin for straight lengths of line is constructed of a malleable iron casting with $\frac{3}{4}$ inch wrought iron or steel stud screwed into its base. The stud goes through the cross-arm, and the casting is mounted on the arm and carries the insulator. On curves and turns a bolt is passed entirely through the cast-iron part of the pin and is thence passed down through the arm with a nut and washer underneath. The length of the $\frac{3}{4}$ inch through bolt for this strain pin is about $16\frac{1}{2}$ inches; the length of the cast-iron section mounted above the cross-arm is $8\frac{3}{4}$ inches; the flange of the casting that rests on the arm is $3\frac{3}{4}$ inches by 5 inches; the top of this casting is $1\frac{3}{8}$ inches in diameter with $\frac{1}{4}$ inch threads for the insulator.

Two types of porcelain insulators with brown glaze are used. The form most largely used is molded in a single piece with double petticoats. The newer type of insulator is made in three parts and then cemented together. The insulators are fastened to the pins by Portland cement poured into the pin hole of the insulator while the free pin top is held in a central position. The line wires are tied to the sides of the insulators, but the insulators are designed for either top or side tying.

The line conductors are made up of solid, hard-drawn bare copper of 98.5 per cent conductivity. One of the three-phase circuits from the Spier Falls plant contains

three four-pin cross-arms per pole with wires spaced 36 inches apart. Two conductors of a circuit are mounted on the two insulators which are on that half of a top cross-arm on one side of its support. The remaining conductor of this line is carried on the insulator at the end of the next lower arm and immediately below the outer of the two wires of that line on the top arm. This method of stringing leaves the inner insulator on the same end of the middle arm and the two insulators on the corresponding end of the third or bottom cross-arm for another three-phase line. The six conductors on the opposite side of the pole are arranged in a like way.

The conductors are transposed one third of a turn for each section of 130 poles. Thus each wire passes through a complete circle every 7.5 miles, there being 52 poles per mile of straight line.

In crossing several railway tracks special constructions are employed. The poles of the double line are 9 feet apart. The top cross-arm is 16 feet in length, the middle arm 10.5 feet, and the lowest arm 14 feet long. The towers are constructed of Georgia pine and chestnut. Each is 66.5 feet high from the base to the upper side of the top cross-arm and is set 10.5 feet in the earth. The wood in the towers is treated with carbolineum, while all plates and bolts on the subterranean parts are coated with coal tar.

Guard wires are not used for lightning protection on any of the transmission lines, and arresters are employed only at the central stations, sub-stations, and switch houses.

Where the conductors enter or leave a generating or sub-station a weather shield is provided. The shield is constructed of boards on the side of the structure which

the high-voltage lines enter, and is provided with an inclined roof and gutter, so that water falling on the roof is conducted off the sides and falls clear of the wires.

At central stations, sub-stations, and switch houses throughout the transmission system the arrangement of the circuits and switches is such that the attendants can connect any particular generator or step-up transformer to any circuit, any transmission circuit to any step-down transformer, and any distribution line to the bus-bars supplied from any generator.

The 40,000 (nominal) horse-power developed by the two plants is transmitted to Troy, Albany, Schenectady, Cohoes, Lansingburg, Ballston Spa, Saratoga, Fort Edward, Sandy Hill, and Glens Falls, with an aggregate population of 300,000. The power is mainly utilized by manufacturing and electric railway properties. The General Electric Company alone has contracted for 10,000 horse-power.

LIBRARY
OF THE
UNIVERSITY
OF
CALIFORNIA

INDEX

LIBRARY OF THE

THIS BOOK IS DUE ON THE LAST DATE
STAMPED BELOW

AN INITIAL FINE OF 25 CENTS

WILL BE ASSESSED FOR FAILURE TO RETURN THIS BOOK ON THE DATE DUE. THE PENALTY WILL INCREASE TO 50 CENTS ON THE FOURTH DAY AND TO $1.00 ON THE SEVENTH DAY OVERDUE.

OCT 30 1934

NOV 13 1934

SEP 19 1938

MAR 4 1941M

LD 21-100m-7,'33

YC 19609

Hutchinson
158898
TK
48